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MARINE EXPOSURE TESTS ON STAINLESS STEEL SHEET

By Willard Mutchler

National Bureau of Standards

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INTRODUCTION

Tidewater and weather-exposure tests on metals used in aircraft have been conducted by the National Bureau of Standards since June 1926. The investigations have been sponsored by the National Advisory Committee for Aeronautics, the Army Air Forces of the War Department, and the Bureau of Aeronautics of the Navy Department. This work embraced three distinct research projects dealing respectively with (1) aluminum-rich alloys, (2) magnesium-rich alloys, and (3) stainless steels.

Previous publications (references 1 to 16) have contained the partial or final results of separate related programs of research. The present paper is a final report on the corrosion tests of stainless steel sheets included in the marine exposure programs from 1938 to 1945. Data on these panels after their first or second year of exposure are contained in previous publications (references 12 to 15).

PROCEDURE

Purpose.- The initial and principal objective of the present study was to establish the relative resistance to corrosion of chromium-nickel alloys of the 18:8 type with and without small additions of columbium, molybdenum, and titanium as alloying elements. Addenda were later made to obtain information on the effect of locality of exposure, of shot-welding, of various surface treatments and finishes, and of contact with dissimilar metals.

Materials.- The steels were in sheet form and of 10 types (table 1), with respect to nominal chemical compositions, comprising 40 different heats. The majority of the sheets were cold-rolled, having tensile strengths between 150,000 and 200,000 psi, and polished surfaces passivated by immersion in 20 percent nitric acid at about 60° C for 30 to 60 minutes.

Types of panels.- The exposure panels, each 14 inches long and 4 inches wide were all prepared by the cooperating manufacturers and were of three types: (1) ordinary sheet; (2) shot-welded and assembled from three sections, each with an overlap of $1\frac{1}{2}$ inches on which was a double row of four welds, each spaced approximately 3/4 inch apart (fig. 1); and (3) having dissimilar metals in contact, with the main sheet (Alloy "A") sandwiched between two strips (Alloy "B"), 1 by 4 inches, joined to it by riveting (fig. 1). Area ratios for the main sheet and the strips were 1:7 and 7:1 for each combination.

Panels with electric-resistance shot-welds were usually protected at the faying surfaces with petrolatum pastes containing aluminum or copper powders. The surfaces of each weld were rubbed lightly with emery to remove the oxide film which forms at the high welding temperatures.

Panels were usually prepared in sets of eight duplicates to permit the exposure of four to tidewater, three to weather, and the retention of one for storage as a control in a dry atmosphere. Prior to exposure each was degreased in trichloroethylene vapor and then was successively washed with carbon tetrachloride and alcohol.

Methods of exposure.- The exposure racks containing most of the panels were located at the U.S.Naval Air Station, Hampton Roads, Va. This area is representative of a temperate climate with marine conditions. During the first $2\frac{1}{2}$ years of exposure the racks were situated (fig. 2A) in an inlet of semi-brackish water named Boush Creek. They were then moved to a lagoon (fig. 2E, F) where the salinity (table 2) of the water was somewhat higher. At that time the simultaneous exposures of panels at Kure Beach, N. C., (fig. 2B) and Chapman Field, Fla., (fig. 2C, 2D) were begun. Laboratory corrosion tests were also made on a few of the shot-welded samples.

The weather racks at the Boush Creek site (fig. 2A) were directly over the water, with the panels suspended at an angle of 45°, and between 6 and 11 feet above the mean tide level. They faced northeast from June 1938 to April 1939, and southeast thereafter until they were transferred to a temporary lagoon site (fig. 2E) in October 1941. A branch railway about 1/8 mile from the Boush Creek location resulted in light deposits of soot on the skyward surfaces of the panels. During periods of storm or high winds the under surfaces were occasionally wet with spray.

At the lagoon (fig. 2E) the racks faced southeast, were on land approximately 25 feet from the water, and were sheltered by a high earth embankment some 50 feet to their rear. The weather racks at Kure Beach, N. C., (fig. 2B) were also on land, approximately 25 feet from the ocean, faced east by north, and received spray during severe storms. The weather racks at Chapman Field, Fla., faced south and presumably were located on land near Biscayne Bay. Panels at both localities were suspended at an angle of 45°.

The tidewater racks at Hampton Roads, Va., were situated in Boush Creek (fig. 2A) from June 1938 to November 1940, and in the lagoon (fig. 2E, 2F) thereafter until June of 1944. The panels were suspended vertically in the middle of the tide range, which averaged $2\frac{1}{2}$ feet, so that they were completely immersed at high tide and out of water at low tide for approximately 5-hour periods twice daily. The mean monthly temperatures of the water from December through April was about 2° F higher than the air temperature, and about 4° F lower during the remaining months. The approximate mean monthly temperatures of the water were (data from U.S. Weather Bureau records of 1881):-

January	38°
February	40°
March	47°
April	52°
May	70°
June	77°
July	84°
August	81°
September	78°
October	69°
November	51°
December	49°

Panels in the tidewater racks at Hampton Roads were mounted edgewise (figs. 3 and 4) with the flat surfaces held upright between bakelite separators, each 3 inches long. The separators were so designed that only four small projecting "points," each 0.008 square inch in area, came in contact with the panel; hence adequate drainage was assured. The panels and separators were suspended, on bakelite-covered monel metal rods which, in turn, rested in slotted arms of monel metal angle supports. Monel metal springs, next to the outermost separators on each end, maintained close contact of the separator "points" with the panels.

Panels exposed to tidewater at Hampton Roads gradually became covered with a mixture of green organic plant growths (mostly algae) and colloidal mud, the thickness of which seldom exceeded 1/16 inch. Animal organisms were relatively few in number, and consisted principally of barnacles.

At Biscayne Bay, Fla., (fig. 2C, 2D) the tidewater panels were mounted at an angle of 45°, faced south, and were bolted to wood supports with bakelite insulators intervening. Although the temperature of the water was uniformly higher than at Hampton Roads, the quantity and types of marine growth which adhered to the panels were quite similar.

At Kure Beach, N. C., the panels were exposed in a canal, which crossed Cape Fear, through which sea water was pumped more or less continuously at a rate of flow of from 1 to 2 feet per second. The panels were continuously immersed, at a depth of from 3 to 4 feet. Marine growths were much more abundant, and of more varied species, than at the other two stations, and attained a total thickness of between 1 and 2 inches. These organisms were responsible for some of the very severe corrosion which occurred on certain alloys at that locality.

Methods of Evaluating Corrosion.- All panels were examined macroscopically to determine the extent of corrosion, and were photographed at one-half natural size. Microscopic examinations of a number of cross sections revealed that in most instances the pits were too widely scattered and too shallow to permit accurate measurements of their depth and distribution.

A method entailing the preparation of a plastic replica of the surface recently developed at the National Bureau of Standards for evaluating surface finish (reference 17), was used experimentally on a few samples. The results were sufficiently promising to warrant continued research, now in progress, to determine the applicability of the method as a means for evaluating the degree of pin-hole corrosion, which serves as a function of surface roughness on the stainless steel sheets. A beam of light is transmitted through the plastic replica maintained in oscillating motion, thence to a photo-electric cell. An alternating electronic voltmeter registers the average variation in the voltage. This serves as a measure of the surface roughness arising from pitting.

Tensile tests were used to a limited extent, but the method most frequently employed to evaluate the damage from corrosion involved determining the approximate fatigue limits (reference 15) on the steels before corrosion and after exposure for different lengths of time.

The tests were made in flexural fatigue testing machines of the fixed deflection (constant strain) type, developed by G. N. Krouse for sheet. Twelve specimens (fig. 5) were cut from each exposed panel in the direction of rolling, thus precluding corrosion on the cut edges. The edges of these specimens were carefully rubbed with Aloxite paper until the edges were very slightly rounded and no burrs were detectable by touch.

Each specimen, before testing, was calibrated as its own dynamometer by measuring its deflection when loaded with dead weights (fig. 6) and by adjusting a variable throw crank to correspond to this deflection. Specimens were loaded at the free end and vibrated as a cantilever beam by means of the variable-throw crank and a connecting rod (fig. 7). The cycle of stress represented a complete reversal from a maximum tensile stress to a compressive stress of equal magnitude. The value selected for the fatigue limit was the stress within 800 psi of the next highest stress which resulted in failure, provided at least two "runs" past 10 or 20 million cycles had been made. The machines operated at approximately $2\frac{1}{2}$ million cycles of stress every 24 hours.

RESULTS

Effect of chemical composition.- The sheets initially exposed to the tidewater and weather at Hampton Roads, Va., (table 1, note b1) were approximately 0.019 inch thick with bright-rolled (2-B) surface finishes. They contained 17 to 20 percent of chromium, 7 to 10 percent of nickel, and, in some instances, small amounts of molybdenum, titanium, or columbium. Steel E, of the 16:1 type, was exposed with a pickled (No. 1) surface finish. A second series of thicker (0.030 to 0.075 in.) panels (table 1, note b5), of comparable chemical compositions and with similar, and other degrees of surface finish were later exposed.

The panels exposed to the tidewater for 3 years (fig. 8) exhibited only a very few areas of rust, most of which occurred adjacent to the overlapped edges on the shot-welded panels. Examination of the surfaces at low magnifications revealed widely scattered, shallow, "pin-point" pits, around which rust was rarely visible. The wide discrepancy of results of the visual examinations, made by a number of different observers, indicated that it was virtually impossible to rate these steels by that method according to their relative susceptibility to corrosion. Steel E, however, exhibited numerous 'pin points' to approximately 1/8-inch diameter areas of superficial rust, which occurred during the first 6 months of exposure, and were not much worse after 36 months of exposure. It therefore, was consistently rated inferior in its corrosion resistance to steels of the 18:8 type.

Panels exposed to the weather became covered more or less uniformly with superficial, but adherent rust deposits. The rust gradually became thicker with more prolonged exposure, but at the end of the third year (fig. 8) was still relatively thin, and removable by the application of a suitable metal cleaner and polisher.

At intervals of 6 months or less the rust was cleaned from some of the panels (steel A1, fig. 8) with a commercial cleaner. This is a paste-type cleaner containing a grit, which leaves a water repellant wax film on the metal after polishing. Minute pits were observable under most of the rusted areas after this cleaning. Such periodic cleaning did not prevent corrosion, but appreciably retarded the rate at which rust formed. A panel, for example, cleaned after 30 months of exposure showed less rust at the end of the 36th month (fig. 8), than a similar panel, not cleaned, after its initial 6 months of exposure.

Periodic inspections during the exposure tests consistently revealed the steels containing molybdenum to be very much less rusted than the others, while Steel E exhibited the most rust. Steels of the ordinary 18:8 type, and those containing titanium or columbium were adjudged intermediate in their resistance to corrosion, but a steel (BD-1) containing both molybdenum and columbium was somewhat less rusted.

In general, panels exposed to the weather at Hampton Roads subsequent to the insertion of the initial panels (table 1, note b1) were less rusted than these, probably owing in part to the relocation of the racks at a greater distance inland from the sea water. The quantities of rust on the steels of different compositions, however, remained in the same relative order.

Results of the fatigue tests on the steels initially exposed are given in a number of diagrams (figs. 9 to 15). The small symbols on these diagrams each represent a test on a single specimen, while the large symbols denote the approximate flexural endurance limits (10^7 or 10^8 cycles). Failures of the exposed samples in the fatigue testing machines occurred, with but a few exceptions, in less than $2\frac{1}{2}$ million stress cycles.

Curves summarizing the results on panels exposed at Boush Creek, Hampton Roads, Va., (figs. 16, 17) reveal that the panels which were exposed to the weather usually suffered a greater loss in fatigue limit than did corresponding ones exposed to the tidewater. The reverse was true for panels exposed at the lagoon (fig. 17), probably owing to the more sheltered location of the weather exposure racks. The average rates of corrosion of all the exposed panels (fig. 17) was most rapid during the first 6 months of exposure, continued at a slow rate for the succeeding 18 months, and then was accelerated somewhat during the final 12 months. Irrespective of whether the panels were exposed to the weather or tidewater, the average variation in the percentage of loss in the fatigue limits was only approximately ± 3 percent from the mean value.

Data from the fatigue tests, plotted to permit a direct comparison of the effect of chemical compositions (fig. 18), agree in general with the results of the macrographic examinations. The steels containing molybdenum or titanium proved the most resistant to corrosion; while the straight 18:8 steels, those containing columbium (containing less columbium than is now recommended), and the one 16:1 type steel were of decreasing corrosion resistance in that order. It should also be noted that the curves for steel E are conjectural, particularly for the first 6 months of exposure, since no material was available on which to determine its fatigue limit in the initial condition. A stress value (80,000 psi) somewhat higher than determined for the other steels was assumed for calculating the percentage losses (fig. 18), because the Vickers hardness number for this steel was much higher than for any of the others.

The following data, obtained by the plastic replica method for evaluating surface finish (reference 17), agrees reasonably with the results of the visual examinations and the fatigue tests. The higher the values, given in millivolts $\times 10^{-1}$, the greater the degree of surface roughness and pitting.

Surface Roughness by Plastic Replica Method - millivolts $\times 10^{-1}$

Exposed 36 months at Boush Creek

Steel	Uncorroded	Tidewater	Weather
A-1	6.7	29.7	41.0
D-5	8.5	24.3	23.2
B-1	12.2	12.2	15.2

Two steels were exposed at Boush Creek, one containing 3.7 percent molybdenum (B-2), and the other 2.5 percent (B-7). Periodic visual inspections throughout the 3-year exposure indicated that the steel with the lower molybdenum rusted somewhat more rapidly. The difference was so slight, however, as to be adjudged immaterial for most practical applications.

Fatigue test data on two steels exposed to the weather for 1 year at Kure Beach, N. C., (table 3), indicated that a steel (F) containing 18 percent of chromuim, and 4 percent each of nickel and manganese, was someshat more resistant than an ordinary 18:8 steel (A-15). Tensile tests on the same panels failed to reveal any difference in the corrosion. The differentiation shown by the fatigue tests was ascribed to their greater sensitivity to notch effects, as exemplified by shallow surface pits.

Two straight 18:8 type steels, one (A-9) with a tensile strength of 190,000 psi, and the other (A-5) with 100,000 psi, along with a 1/4-hard-rolled steel (B-3) having a tensile strength of 120,000 psi were exposed simultaneously at the three localities. The fatigue tests (fig. 22) revealed that steel A-9 usually was the least susceptible to corrosion. Steel A-5 was somewhat more resistant to corrosion than steel B-3 under all the conditions of exposure, except in the sea water at Kure Beach, N. C.

After the first sheets were withdrawn from the racks at Hampton Roads and the flexural fatigue data had revealed an appreciable loss in endurance limit on the corroded samples, it was thought that losses of such magnitude might be characteristic only for sheet. A series of R. R. Moore fatigue specimens were therefore prepared from a 5/8 inch rod, for exposure to the weather. The chemical analysis of this rod yielded the following constituent percentages: 19.09, chromium; 9.15, nickel; 0.05, carbon; 0.39, manganese; 0.010, phosphorus; 0.015, sulphur; and 0.29, titanium.

The fatigue specimens were machined to a minimum thickness of 0.2 inch in the reduced section, were polished successively on 1/0, 2/0, 3/0, and 4/0 emery papers, and then were passivated for 1 hour in a 20-percent solution of nitric acid by volume at 60° C. They were exposed to the weather at Hampton Roads on May 27, 1942. The endurance limits obtained before and after corrosion were as follows:

Exposure Period	Endurance Limit (psi)
Initial, unexposed	75,000
1 year	<55,000
3 years	52,000

Corrosion of shot welds and of faying surfaces.- The resistance to corrosion of the shot welds on representative steels was determined by means of laboratory, as well as exposure, tests. The steels tested in the laboratory were those designated A-1 (18:8), B-1 (3.7 percent of molybdenum), C-1 (0.5 percent of titanium), and D-5 (0.5 percent of columbium). The welded samples were immersed for 9 months, either intermittently or continuously, in a solution containing 1 percent of magnesium chloride and 4 percent of sodium chloride, at a pH of 7.0, and at room temperature. No evidence of failure on any of the welds was observed in these tests.

Continuous immersion of similar samples was also made, for 120 days, in a boiling solution of the same composition, except that the pH was adjusted to 3.0 by the addition of ferric chloride. The unwelded portions of steels A-1, C-1, and D-5 stained much more in the corroding solution than steel B-1. Steel D-5, which contained columbium, was the most severely attacked, and one sample developed very severe pits on parts of the surface away from the welds.

After 15 days of exposure in the boiling chloride solution exposed cross sections cut through some of the welds on steels C-1 and D-5 (figs. 23a and 23b) revealed severe corrosion. At the end of 120 days two of the welds in the titanium-bearing steel C-1, had failed (figs. 23c and 23d); while welds in the other samples contained only superficial pits.

Shot welds on panels exposed to the tidewater at Hampton Roads, Va., in general, appeared on visual inspection to be no more severely pitted than the remainder of the sheets. On panels exposed to the weather, however, there was a marked tendency toward slightly heavier deposits of rust on the welds. Welds on the molybdenum-containing steels were the least rusted; while those on the 16:1 type steel E were the most rusted.

Tensile tests were made on single shot welds, of which there were 16 on each welded panel, after exposure at Hampton Roads. Only a few of the welds showed marked losses in the breaking loads or exhibited evidence of severe rusting after prolonged exposure. These failures were probably related to specific conditions occurring at the moment of welding, rather than to the inherent chemical and microstructural characteristics of the sheets.

Representative results of the tensile tests on a few of the steels (fig. 24) reveal that, except for isolated instances on corroded welds, the range in breaking loads for the single welds was within narrow limits. The highest values were obtained on steel E. Tests made at the E. G. Budd Manufacturing Company on similar welds in this 16:1 type steel, showed that they would withstand a twist of only 10° before failure; whereas welds in the 18:8 type steels withstood a twist of 90° before failure. Shot welds in alloys corresponding to steel E probably would not prove as satisfactory as the austenitic type alloys for highly stressed structures.

On all the 18:8 type steels to which petrolatum grease was applied at the faying surfaces prior to shot welding, little or no corrosion was noted at the overlaps after 3 years of exposure to tidewater or the weather at Hampton Roads (figs. 25 and 26), and most of the grease was still _in situ_. When such greasing was omitted, however, from 50 to 80 percent of these areas were covered with rust. On steel E some rusting occurred at the faying surfaces, even though grease had been applied.

Effect of surface treatments and finishes.- Steels containing 2.7 (B-7) or 3.7 (B-3) percent of molybdenum were surface treated, prior to exposure, in the following ways:

1. (Pi) - *Pickled.*- Treated for 20 to 30 minutes in a solution containing 20 percent of nitric acid and 4 percent of hydrofluoric acid, by volume, at 60° C.

2. (Pa) - *Passivated.*- Treated for 60 minutes in a solution of 20 percent nitric acid at 60° C.

3. (Pi-Pa) - *Pickled, passivated.*- As in (1) and (2).

4. (Pa-Pr-Pa) - *Passivated, pre-surfaced, passivated.*- Passivations as in (2). The pre-surface (pre-pitting) treatment consisted of immersion for 30 minutes in a 10-percent ferric chloride solution at room temperature.

5. (Pi-Pa-Pr-Pa) - *Pickled, passivated, pre-surfaced, passivated.*- Same treatments as in (4) with a pre-pickle as in (1).

After 3 years of exposure to the tidewater and weather at Hampton Roads, Va., all panels were inspected by four observers and rated numerically with respect to the quantity of corrosion present (table 4). For panels exposed to the weather the rust deposits served as a reliable criterion of corrosion while those exposed to tidewater exhibited only scattered and minute surface pits, which rendered judgement much more difficult. The ratings indicate, particularly on the panels which were exposed to the atmosphere, that those given the pickled-passivated treatment exhibited the least rust. Panels which were passivated, pre-surfaced, and passivated (treatment 4) exhibited more rust than others given the same treatments after pre-pickling (treatment 5). The beneficial effect of pickling prior to passivation also was noted on steel A-9. Panels of this 18:8 type steel which were passivated only, exhibited considerably more rust after exposure to the weather than other panels which were pickled, then passivated.

It may be concluded, therefore, that pickling prior to passivating treatments tends to improve the resistance to corrosive attack, but that the more elaborate systems of passivation coupled with pre-surfacing afford no more protection than does a single passivation without prepickling.

A number of steels of different chemical compositions and commercial surface finishes (table 1, note b5) were exposed at Hampton Roads. On panels exposed to the tidewater, for periods up to 3 years, areas of superficial rust occurred occasionally on panels having the duller surface finishes (designated No. 2-D and No. 1). On specimens exposed to the weather, the amount of rust on panels of a given composition correlated with the degree of surface polish (fig. 27).

The rust tended to form on isolated areas, approximately 1/2 inch in diameter, on panels having the No. 1 and No. 2-D finishes. The deposits were thicker on the No. 1 than on the No. 2-D finish, and were noticeably heavier on these two finishes than on the others. Although the rust on the surfaces having Nos. 2-B, No. 4, and No. 6 finishes was, in general, much more superficial, the number of individual areas of rust were more numerous and of smaller size, seldom exceeding 1/8 inch in diameter. The amount of rust on the No. 2-B and No. 4 finishes was approximately the same, but in general tended to be somewhat less on the No. 6 finish. A No. 7 finish, the highest degree of polish of the panels tested and applied only to the straight 18:8 steels, exhibited the least rust.

Certain of these panels were cleaned periodically with a commercial cleaner. On the two surfaces having dull finishes, Nos. 1 and 2-D, the cleaner usually removed the rust only partially even after vigorous rubbing. Rust on the surfaces having Nos. 2-B, 4, and 6 finishes could be entirely removed without the application of much pressure. Rust from surfaces with the No. 7 finish was readily removed with relatively light rubbing.

A few panels of the 18:8 type were exposed to the tidewater at Hampton Roads, Va., after applying hand-brushed clear varnish coatings. The coatings included two applied by the E. I. DuPont de Nemours Co., and two applied by the Hercules Powder Company. The coatings all began to peel from the sheets during the first year and were almost entirely off at the end of the second year. Most paints are not adherent, on polished stainless steel surfaces.

Contacts with dissimilar metals.- Steel C-1, stabilized with 0.5 percent of titanium, was the one used on the panels having stainless steel exposed in contact with aluminum or magnesium alloys at Hampton Roads. The first year of exposure in the tidewater racks (figs. 28 and 29) showed that the four aluminum alloys investigated, commercially known as 24S-T, Alclad 24S-T, 53S-T, and 52S-1/2H, were highly anodic. They were severely corroded, and corrosion products formed in large quantities between the faying surfaces of the steel and the aluminum alloys, especially when the surface areas of the aluminum alloys were small as compared with the steel.

Both the macroscopic and microscopic examinations revealed that alloys 24S-T and Alclad 24S-T were the most severely attacked, with 53S-T somewhat less so, and 52S-1/2H the least. This does not necessarily indicate the order of the potential differences involved since the 52S-1/2H and Alclad 24S-T alloys are inherently the most resistant to corrosion.

Identical couples exposed to the weather (fig. 30) corroded similarly to those in tidewater but at a much slower rate. In some instances (fig. 30, alloy 24S-T) the accumulation of corrosion products at the faying surface resulted in sufficient stress to break off rivet heads. Stress-corrosion cracks, for the same reason, were present on some of the 24S T exposed to the weather or tidewater, and on the Alclad, 24S-T strips exposed to tidewater (fig.31C) attached to stainless steel panels.

A series of panels was included, in the tidewater exposure only, in which stainless steel strips were insulated from the aluminum alloy main panels by the following mediums:

1. No insulation

2. Four sheets of 0.002-inch thick aluminum foil, Navy Specification AC11074, Grade A, with aluminum washers, Type AN960-A-6 under the Type AN430-D Thomson Head, anodized 17S-T rivets.

3. Cellulose tape

4. Grade A cotton fabric, Navy Specification AC6-97 impregnated with a bakelite-type seam compound.

5. Grade A cotton fabric impregnated with soya-bean oil and a clear spar varnish (1:1 ratio), Navy Specification V11-c.

6. Grade A cotton fabric impregnated with a bitumenlike substance.

The aluminum alloy main panels were painted with one coat of primer and two coats of varnish, pigmented with $1\frac{1}{4}$ pounds of aluminum powder per gallon. The stainless steel strips were not painted, nor were some panels of Alclad 17S-T alloy. Aluminum alloy panles which were painted included Alclad 17S-T, anodized 17S-T, anodized 24S-T, and 52S-1/2H.

The panels were removed from the tidewater racks after 2 years of exposure (fig. 32) and the macroscopic examination revealed:

1. The stainless steel strips showed no attack on any of the panels.

2. Rivet heads were practically unattacked on (a) all unpainted Alclad 17S-T panels, irrespective of the system of insulation, and (b) all panels where the insulation was aluminum foil.

3. As judged by the quantity and distribution of the corrosion products around the edges of the stainless steel strips, the best systems of insulation were the aluminum foil, and the impregnated cotton fabric systems. Soya-bean oil plus varnish and bakelite-type impregnations were somewhat more

effective than the bituminous-type. The cellulose tape and non-insulated systems were ineffective.

4. Paint failures, extending 3/8 inch inward from the edges, were prevalent on all except the 52S-1/2H panels. On painted panels, less corrosion products were present on the 52S-1/2H and Alclad 17S-T than on the remaining alloys.

5. Painted and anodized 17S-T rivet heads were fairly severely attacked on painted Alclad 17S-T, 17S-T, and 24S-T alloys, especially on the latter two. The number of heads on which attack occurred, however, was least for the aluminum foil, and most for the cellulose tape and non-insulated systems.

6. "Spotting" of rivet heads with two coats of aluminum paint proved ineffective where the heads were adjacent to stainless steel. Failure occurred on upward of 50 percent of the painted heads, probably augmented by poor adherence of paint to the steel, and the resulting attack often was more severe than on unpainted rivet heads.

7. Probably none of the systems of insulating proved as effective as may be desired. Painting of the aluminum portion definitely removed much of the anodic (protective) effect of the panel upon the rivets. Where the dissimilar metal is much the smaller in area, as on the present panels, it is suggested that more effective insulation might be obtained by painting the smaller strips, rather than the larger panel areas, if adherent paint were available.

Two unpainted magnesium alloys, Dowmetals M and H, were very severely attacked when coupled with stainless steel, especially when exposed to tidewater at Hampton Roads. Immediately after the first tidewater had covered these panels, violent bubbling of the water occurred, and the reaction was audible at a distance of approximately 15 feet. An adherent white corrosion product was deposited on the steel, which attained a thickness of 0.004 inch on the second day of exposure (fig. 33), at which time the first set of unpainted panels was removed. The white deposit gradually disappeared, and the underlying steel was found unattacked. The Dowmetal M was attacked somewhat more rapidly than the Dowmetal H. The unpainted panels were removed from the tidewater racks after 1/15, 1, 3, and 12 months, while panels painted prior to exposure (fig. 34) were removed from the tidewater racks after 1, 3, $7\frac{1}{2}$, and 12 months. The paint schedule consisted of 1 coat of zinc chromate primer and 3 coats of aluminum-pigmented varnish (Navy Specification V10-d).

Unpainted panels exposed to the weather corroded at a much slower rate than those exposed to tidewater, but between the first and second years corrosion products at the faying surfaces (fig. 31A and 31B) were sufficient in quantity to cause stress corrosion cracking of the stainless steel strips. The paint between the faying surfaces on the painted panels afforded excellent protection, and severe corrosion at the couples was not noted until after the second year of weather exposure (fig. 34).

A number of panels (Steel A-6) were suspended in the tidewater racks between separators of wood, glass, hard rubber, bakelite, monel metal, copper, or brass. Panels were suspended by each supporting material, by the (1) "four-point" method used in the main programs, and (2) with contact established with the steel over an area of approximately one square inch. The metallic separators were arranged, in some instances, to permit a complete electric circuit through them and the test panels.

The tests revealed that any of the materials were suitable for suspending stainless steel in sea water, provided the "four-point" method was used, and that the suspending medium was kept in very close contact with the steel. Where the areas of contact (fig. 36) were 1 square inch and no provision was made for drainage, the "inert" separators, such as wood, glass, hard rubber, and bakelite were relatively less satisfactory. Inasmuch as the areas of contact were not optically flat, a sufficiently close contact between the separators and the steel was not possible even with the aid of monel springs.

The severity of the corrosion on the steel panels was increased when the wood and bakelite separators were painted with either clear or aluminum-pigmented marine spar varnishes. Such vehicles, once permeated, apparently retained saline moisture and oxygen which affected the corrosion on the steel. No evident electrolytic corrosion occurred on the stainless steel panels in contact with the monel, brass, or copper separators, whether or not the system of mounting permitted the completion of an electric circuit. It is deemed unwise, however, to use dissimilar metals for supports in tidewater tests, since they may influence the rate of attack on the panel. Corrosion products which formed on the copper and brass separators, for example, may have resulted in part from electrolytic action.

Effect of locality of exposure.- It has been previously stated that, at all localities, corrosion products accumulated in greatest abundance on the under, or earthward, surfaces of the stainless steel panels exposed to the weather. This observation has been made by many investigators, and is regarded as characteristic of most metals, whether the weather exposure conditions be classifiable as marine, inland rural, or industrial. No entirely satisfactory theory has been promulgated to account for this behavior, but the cleansing action of rain water on the skyward surfaces is generally accepted as constituting one factor in the retardation of corrosion.

The corrosion products which form on the earthward surface usually are neither continuous nor of uniform thickness. Comparatively heavy depositions approximately circular in area, and varying in size from points to 1/2 inch diameter, usually are distributed more or less uniformly. On the rest of the surface the products are either more superficial or absent. Analogous surface appearances are rarely achieved in the various types of laboratory tests.

However, such surface appearances were duplicated at the National Bureau of Standards in rather simple and purely qualitative experiments. Strips of sheet metals approximately 2 feet long and from 1 to 3 inches wide, were bent rectangularly at each end. One was placed in a beaker of boiling water, the other in a beaker of ice water, to assure a temperature gradient. The horizontally situated sheet was sprayed with a dilute solution of sodium chloride on its top and bottom surfaces. As soon as drying was complete the spray was repeated. Drying occurred at a slower rate on the under surface. Corrosion products formed initially, usually in a narrow band less than 1/2 inch wide, at a location nearest the hotter end, and on the under side. With repeated sprayings and alternate dryings the width of the band gradually increased toward the colder end, and finally attained its apparent maximum width.

This behavior is believed to be analogous to that which results in outdoor weathering. The phenomenon is suggestive of a type of electrolytic cell, perhaps of the oxygen-concentration variety, which probably attains its maximum activity during the periods of retention of films of moisture having certain critical ranges of thickness. The films ultimately become discontinuous and agglomerate into droplets owing to surface tension. The length of time that the critical films are present, probably determines the rate at which the corrosion products form.

In outdoor weathering the formation of corrosion products is therefore largely dependent upon the frequency of rainfalls, or of condensations associated with the dew-point, the humidity, and the rate of drying engendered by sunlight. The sun hastens the drying on the skyward surface of the exposure panel, much more than on the earthward surface. It has been shown (fig. 17) that minor changes in location at a single locality may be a determining factor, as to whether corrosion is more severe on the stainless steel panels exposed to the weather, or on those exposed to tidewater.

The results of the fatigue tests on panels exposed simultaneously (Steels A-5, A-9, and B-3) at Hampton Roads, Kure Beach, and Chapman Field (figs. 19, 20, 21, and 22) already have been given with respect to the behavior of each steel. The average data for the three steels (fig. 35), plotted on the basis of percent loss of initial endurance limit, reveals more informatively the rates of corrosion as related to the locality of exposure. Panels exposed to the weather at Kure Beach exhibited more loss in fatigue limits than those exposed under any of the other marine conditions. These curves show that after exposure to weather or tidewater at Hampton Roads or Chapman Field, or after exposure to sea water at Kure Beach, the average variation in the percentage of loss in the fatigue limits was within $\pm 2\frac{1}{2}$ percent. This compares closely with the value of $\pm$ 3 percent (fig. 17) obtained at the Hampton Roads station on a larger number of specimens initially exposed on a different date.

In general, the surface appearance was very similar on all the stainless steel panels exposed to the sea water at the three localities and rust discolorations usually were not present. The only exceptions occurred at Kure Beach, where the two straight 18:8 steels were severely rusted under the areas of contact with their bakelite supports (fig. 36), and along longitudinal streaks extending outward from the same source. Such areas were discarded in machining the specimens for the fatigue tests. Only one panel (Steel B-3) was left in the sea water at Kure Beach for the 12-month exposure, and it contained several pits obviously associated with the action of sea-organisms.

The panels exposed to the weather at Hampton Roads and Chapman Field exhibited superficial rust and were quite alike in appearance, while those at Kure Beach were considerably more rusted (figs. 37 and 38). Surface rust was consistently least on the 1/4-hard molybdenum-containing steel, B-3.

CONCLUSIONS

The conclusions that follow are pertinent to panels exposed for approximately 3 years, under extreme marine conditions, as exemplified by tidewater or weather exposure of metals in close proximity with salt water.

1. Deposits of rust formed in greatest quantity upon the under surfaces of panels exposed to the weather at angles departing from the vertical.

2. Rust deposits usually formed in greatest quantity and thickness within the first 6 months of weathering. Thereafter, for periods up to 36 months, pronounced changes in surface appearance did not ordinarily occur, although the deposits increased slightly in quantity. Minute pits were often discerned beneath many of the rusted areas after cleaning.

3. Rust rarely formed on 18:8 sheet panels exposed to tidewater, particularly those with bright-rolled, or higher degrees of surface

finish, but minute pits were discernible at low magnifications. Similar steels, with dull finishes, among them a 16:1 steel, rusted.

4. Steels approximating the 18:8 composition, and containing from 2.5 to 3.5 percent of molybdenum, exhibited much less rust on weathering than those of the ordinary 18:8 type with or without additions of titanium or columbium. Steels with 3.5 percent of molybdenum rusted slightly less than those with 2.5 percent, but for most practical applications the difference may be regarded as negligible.

5. The quantity and distribution of the rust on sheet panels exposed to the weather may serve as criteria for approximate evaluations of the corrosion, but visual inspections frequently are inadequate for such evaluations of panels exposed to tidewater. A plastic replica method employed for surface analysis appears promising as a means for evaluating the degree of corrosion pitting, after the rust has been removed, as a function of surface roughness. Flexural fatigue tests appeared to be more sensitive than tensile tests as a measure of the damage caused by corrosion.

6. The relative susceptibility to corrosion of the particular sheets under the specific conditions of exposure used in these investigations (fig. 17) could be established by fatigue tests. These revealed a superiority in the steels containing molybdenum or titanium, and an inferiority of the heat-aged columbium-bearing steel and one of the 16:1 type. The relatively narrow range of the loss in fatigue limits (±5 percent) for all the steels except the last two, indicated that the order of susceptibility may be expected to show variations, within the ranges established, on different heats of metal exposed under the same, or other marine conditions.

7. The greatest corrosion damage, as determined by loss in fatigue limits, occurred during the first 6 months of exposure. Thereafter, up to 3 years, the rate of loss usually was very low.

8. The fatigue tests revealed that, at a given locality the damage resulting from exposure to the weather may, or may not, be worse than that resulting from exposure to sea water. Minor changes, such, for example, as the distance inland of weather-exposure panels from the water, the extent to which sea organisms may accelerate the corrosion, and so forth, may be the determining factors.

9. Shot welds, on panels exposed to the weather, tended to be slightly more susceptible to rust formation than other portions of the sheet, on steels of the 18:8 type, and to a somewhat greater degree on a 16:1 type of steel. Shot welds on molybdenum-containing steels are much less susceptible to rusting than on other 18:8 type steels. In tidewater immersions the shot welds do not, as a rule exhibit rust.

10. The strength characteristics of shot welds, in general, remained unaffected after prolonged exposure to the weather or sea water. The relatively few instances in which shot welds exhibited severe corrosion and loss in strength were attributed to slight imperfections in the original welding procedure.

11. On shot-welded panels the most severe rusting frequently occurred at the faying surfaces of the sheets. Applications of appropriate greases, such as petrolatum, were effective in preventing such corrosion.

12. Pickling, prior to passivating surface treatments, tended to improve the resistance of stainless steels to corrosive attack. Systems of surface treatment in which passivation was coupled with pre-pitting, were no more beneficial than passivation which was not preceded by a pickling treatment.

13. On panels exposed to the weather the degree of polish significantly influenced the amount of rusting. Dull finishes (Nos. 1 and 2-D) rusted the most, ordinary commercial polishes (Nos. 2-B, 4, and 6) rusted less, while mirror polishes (No. 7) rusted the least. Rust also tended to develop on dull finished panels exposed to sea water.

14. The adherence of rust to the surface increased as the degree of polish decreased. The superficial rust on polished surfaces may be removed easily by the application of suitable types of metal cleaners, but can be removed only with difficulty, and frequently not completely, from the duller surface finishes. The periodic cleaning of steels exposed to the weather was beneficial, and the wax films left by certain cleaners retarded the formation of rust. The duller surface finishes require cleaning more frequently.

15. The heat-treatment of cold-rolled stainless steels at 440° F for 24 hours resulted in no marked change in extent of rusting on panels exposed to outdoor weathering.

16. Varnishing or painting of polished stainless steel afforded only temporary protection, owing to the fact that paints did not adhere very well, under marine exposure, to such surfaces.

17. Aluminum alloys and magnesium alloys, especially the latter, were highly anodic to stainless steels and were severely attacked when in contact with them. The ratio of the areas is very important and affects the rate of corrosion on the anodic member of the couple. Where the area of the steel is small compared with the light alloy, the minimum corrosion of the latter results from electrolysis, while the maximum corrosion results when the area relationships are reversed.

18. Since the electrolytic couple is effective only when moisture is present, the severity of the corrosion was very much worse for panels exposed to sea water than for those exposed to weathering.

19. Less corrosion is to be expected when aluminum alloys 52S-1/2H or 53S-T are in contact with stainless steel, than with alloys 24S-T or Alclad 24S-T. Accumulations of corrosion products on strips of the latter alloys, exposed to the weather for 2 years, tended to force the strips away from the steel panel and sometimes resulted in stress corrosion cracking on the aluminum alloys and breaking off the heads of rivets used to join the metals.

20. Insulation between stainless steel strips on aluminum alloy panels may be effective in preventing severe corrosion on the aluminum alloy immersed in sea water for periods up to 2 years. Aluminum foil, or cotton fabrics impregnated with soya-bean oil and varnish, or with a bakelite-type seam compound, were suitable for use as insulators. Suitable paint schedules, applied at the faying surfaces, are satisfactory for many conditions of weather exposure.

21. No satisfactory system of insulation has yet been devised for the protection of magnesium alloys which are exposed to sea water in contact with stainless steels.

22. Magnesium alloys nominally containing 1.5 percent of manganese (Dowmetal M) were more severely attacked when in contact with stainless steels than an alloy containing 6 percent of aluminum, 3.0 percent of zinc, and 0.2 percent of manganese (Dowmetal H).

23. On unpainted magnesium alloy panels joined to stainless steel, and exposed to the weather, the accumulation of corrosion products at the faying surfaces may result in the stress-corrosion cracking of the metal forming the strip. Suitable paint schedules, such as a zinc chromate primer with good grades of marine spar varnish, afforded excellent protection for periods in excess of a year.

National Bureau of Standards,
Washington, D. C., August 1945.

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TABLE 1. - PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE STAINLESS STEEL SHEETS

Designation	Commercial type	Thickness (in.)	Surface finish[a]	Exposure[b]	Chemical composition - (percent)							
					Cr	Ni	C	Mn	Si	S	P	Others
A-1[c]	306	0.017	2-B	1	19.99	9.82	0.09	0.49	0.271	0.010	0.019	--
A-1A[c]	306	.015-.030	2-B	1	19.17	8.96	.09	.39	.325	.009	.020	--
A-2[d]	306	.067	2-B	5	19.08	9.05	.092	.52[e]	.57[e]	.012[e]	.022[e]	--
A-3[d]	306	.050	2-D	5	18.86	8.97	.104	.59[e]	.39[e]	.006[e]	.019[e]	--
A-4[d]	306	.045	7	5	18.86	8.67	.05	.55[e]	.36[e]	.009[e]	.021[e]	--
A-5[fd]	306	.016	4	8	18.72	8.68	.06	.54[e]	.36[e]	.008[e]	.018[e]	--
A-6[c]	304	.018	2-B	6	18.54	8.17	.07	.54	.434	.012	.007	--
A-6A[g]	304	.040	2-B	9	18.3	8.4	.08	.33	--	--	--	--
A-7[d]	302	.046	1	5	18.24	9.03	.06	.51[e]	.34[e]	.010[e]	.022[e]	--
A-7A[d]	302	.061	2-B	4	18.	8.	--	--	--	--	--	--
A-8[d]	302	.061	6	5	17.92	8.42	.092	.37[e]	.20[e]	.010[e]	.020[e]	--
A-9[d]	302	.020	2-B[hi]	7,8	17.82	8.25	.118	.52	.39	.014	.017	--
A-10[g]	302	.025	2-B	1	17.8	7.7	.11	.50	.26	--	--	--
A-11[g]	302	.031	2-B	1	17.8	7.5	.09	.66	.31	--	--	--
A-12[g]	302	.020	2-B	1	17.8	7.3	.10	.59	.45	--	--	--
A-13[g]	302	.020	2-B	1	17.6	7.45	.11	.54	.35	--	--	--
A-14[g]	302	.021	2-B	1	17.5	7.35	.11	.59	.38	--	---	--
A-15[j]	302	.060	2-B	3	17.48	8.28	.10	.50	--	--	--	--
A-16[g]	302	.017	2-B	1	17.3	7.4	.10	.58	.40	--	--	--
B-1[c]	317	.018	2-B	1	17.91	11.08	.08	1.41	.364	.006	.015	Mo 3.67
B-2[d]	317	.051	2-B[h]	2	18.80	13.70	.07	1.68[e]	.29[e]	.014[e]	.008[e]	Mo 3.60
B-3[dk]	317	.023	2-B	8	19.00	13.74	.05	1.52	.60	--	.008	Mo 3.40
B-4[d]	317	.043	4	5	18.21	13.04	.06	1.52[e]	.30[e]	.012[e]	.018[e]	Mo 2.94[e]
B-5[d]	317	.051	1	5	17.99	13.28	.056	1.52[e]	.30[e]	.012[e]	.018[e]	Mo 2.94[e]
B-6[d]	316	.076	2-B	5	17.71	10.48	.064	1.07[e]	.17[e]	.009[e]	.018[e]	Mo 2.89[e]
B-7[d]	316	.063	2-B[h]	2	17.79	10.72	.05	1.27[e]	.34[e]	.012[e]	.011[e]	Mo 2.70[e]
B-8[d]	316	.046	2-D	5	17.09	12.89	.056	1.50	.29	.006	.013	Mo 2.70
BD-1[d]	--		2-B	7	18.88	13.60	.06	1.50	.49	.008	.019	Mo 1.87, Cb 0.57
BD-2[d]	--		4	7	18.88	13.60	.06	1.50	.49	.008	.019	Mo 1.87, Cb 0.57
C-1[c]	321	.018	2-B	1	17.56	9.12	.07	.41	.463	.008	.015	Ti 0.50
C-2[d]	321	.041	2-D	5	17.31	11.00	.046	.50	.45	.005	.012	Ti .37
C-3[d]	321	.053	2-B	5	18.42	10.07	.046	1.39[e]	.67[e]	.009[e]	.023[e]	Ti .36[e]
C-4[d]	321	.038	1	5	18.78	10.20	.056	1.34[e]	.65[e]	.005[e]	.022[e]	Ti .27[e]
D-1[dl]	347	.031	2-B	1	18.40	8.56	.08	.50	.47	.020[e]	.010[e]	Cb 0.79
D-2[d]	347	.043	2-D	5	18.06	10.50	.072	1.32[e]	.73[e]	.008[e]	.011[e]	Cb .77[e]
D-3[d]	347	.055	2-B	5	18.64	11.00	.062	1.42[e]	.40[e]	.010[e]	.013[e]	Cb .76[e]
D-4[d]	347	.044	1	5	17.85	10.70	.070	1.23[e]	.58[e]	.009[e]	.015[e]	Cb .64[e]
D-5[c]	347	.018	2-B	1	17.84	9.90	.08	.46	.200	.007	.015	Cb .53
E[m]	431	.018	1	1	17.70	1.62	.08	.72	.518	.021	.012	--
F[j]	--	.063	2-B	3	18.3	4.1	.07	3.95	--	--	--	--

TABLE 1 (Continued)

[a]These commercial finish designations signify: -1, pickled; 2-B, bright cold-rolled; 2-D, dull cold-rolled; 4, standard polish (architectural), ground; 6, standard polish, satin, tampico brush; 7, finish 2-B, plus grit grind to 320 emery, and a final buff, high luster.

[b1]Exposed to tidewater and weather at Hampton Roads, Va., in June 1938. Withdrawals made from weather racks after 7½, 24, and 36 months; from tidewater racks after 7½, 12, 24, and 36 months of exposure.

[b2]Exposed to tidewater and weather at Hampton Roads, in June 1938 and removed after 36 months of exposure; some panels, however, were transferred to the weather racks from the tidewater racks, after 12 months of exposure and remained 24 months in the weather racks.

[b3]Exposed to weather at Kure Beach, N. C., in November 1941, and withdrawn after 12 months.

[b4]Exposed to tidewater at Hampton Roads, Va., in September 1938, and withdrawn after 33 months.

[b5]Exposed to tidewater and weather at Hampton Roads, Va., in November 1940; withdrawn from weather racks after 7, 18, and 36 months and from the tidewater racks after 18 and 36 months. Some of the panels in the weather racks occasionally were cleaned to remove rust.

[b6]Exposed to tidewater at Hampton Roads, Va., in June 1938 and withdrawn after 7½, 12, 24, and 36 months of exposure.

[b7]Exposed to tidewater and weather at Hampton Roads, Va., in June 1940 and withdrawn from the tidewater racks after 12 and 24 months, and from the weather racks after 12, 24, and 36 months of exposure.

[b8]Exposed simultaneously at Hampton Roads, Va., Kure Beach, N. C., and Chapman Field, Fla., in October-November 1940. Withdrawals made after 6 and 12 months at Hampton Roads and Kure Beach, and after 6 months only at Chapman Field.

[b9]Exposed to tidewater at Hampton Roads, Va., in June 1938 and withdrawn after 24 months of exposure.

[c]Material furnished by the American Steel and Wire Company.

[d]Material furnished by the Carnegie-Illinois Steel Corporation.

[e]Ladle analyses; all others represent the manufacturers' check analyses on the billets.

[f]Annealed; ultimate strength 100,000 psi.

[g]Material furnished by the Sharon Steel Corporation, via the Edward G. Budd Manufacturing Company, which cooperated by preparing most of the shot-welded panels.

[h]Some panels surface-treated by means other than simple passivation in nitric acid.

[i]Some panels, after rolling, heated at 440° F for 24 hours, then cooled in air.

[j]Material used in cooperative test with the International Nickel Company.

[k]In the one-fourth hard condition; ultimate strength, 122,000 psi.

[l]Heat-aged to an ultimate strength of 180,000 psi.

[m]Material furnished by the Republic Steel Corporation.

TABLE 2. - CHEMICAL ANALYSES AND CHARACTERISTICS OF THE SEA WATER AT THE EXPOSURE LOCALITIES

Properties and constituents	Hampton Roads, Va.		Chapman Field, Fla. (Biscayne Bay)	Kure Beach, N.C. (Cape Fear).
	Boush Creek[a]	Mason Creek[b]		
Appearance	--	Practically colorless with a small amount of reddish sediment	--	--
pH	8.0	7.6	--	7.7
Specific gravity at 25° /25° C	--	1.018	--	--
Total solids, dried at 110° C	--	24.89	--	--
Calcium (Ca)	--	.30	--	.404
Magnesium (Mg)	--	.92	--	1.292
Sodium (Na)	--	7.61	8.03	10.59
Potassium (K)	--	0.27	--	.403
Sulphate (SO_4)	1.75	1.88	--	2.664
Chloride (Cl)	12.20	13.66	14.47	19.20
Bromide (Br)	--	.038	--	.069
Sum of determined constituents	--	24.68	--	34.62

[a]Tidewater exposure site from June 1938 to Nov. 1940. The analysis was made after a period of heavy rainfall and probably represents the minimum salinity.

[b]Tidewater exposure site from June 1944. The lagoon site, used from Nov. 1940 to June 1944, was a similar inlet, situated about 1 mile away, on Willoughby Bay. The characteristics of its water therefore are believed to conform closely with those at Mason Creek, but the water probably was slightly more saline.

TABLE 3. PHYSICAL PROPERTIES OF TWO STEELS EXPOSED TO THE WEATHER

AT KURE BEACH, N. C., FOR 1 YEAR

Steel designation	Exposure period (mo.)	Tensile Properties			Fatigue limit (psi)
		Ultimate strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)	
A-15	0	166,300	128,000	22.0	69,000
(18:8 type)	12	166,000	129,000	22.0	65,600
F	0	190,000	124,900	27.5	75,000
(18:4:4 type)	12	190,000	127,000	27.0	74,500

Note. - Located 250 yards from ocean beach, facing south at an angle of 30°.

TABLE 4. - STEELS SURFACE TREATED AS INDICATED, EXPOSED FOR 3 YEARS AT HAMPTON ROADS, VA., AND THEN RATED NUMERICALLY BY FOUR OBSERVERS WITH RESPECT TO THE QUANTITY OF CORROSION ON THEIR SURFACES[a]

Steel	Exposure	Surface Treatments[b] and ratings[a]																								
		Pi					Pa					Pi-Pa					Pa-Pr-Pa					Pi-Pa-Pr-Pa				
		Observer No. 1	2	3	4	Av.	Observer No. 1	2	3	4	Av.	Observer No. 1	2	3	4	Av.	Observer No. 1	2	3	4	Av.	Observer No. 1	2	3	4	Av.
B-2	Tidewater	2	3	3	2	2.5	2	1	4	4	2.75				--	--	4	2	2	3	2.75	2	4	1	1	2
B-7	Tidewater	4	2	4	2	3	2	4	3	1	2.5				--	--	2	3	2	4	2.75	2	1	1	3	1.75
B-2	Weather[c]				--	--	4	4	4	3	--	1	1	1	1	--	3	3	3	4	--	2	2	2	2	--
B-2	Weather[d]				--	--	4	4	4	4	4	1	1	1	1	1	3	3	3	5	3	2	2	2	2	2
B-7	Weather[c]				--	--	3	3	4	3	--	1	1	1	1	--	3	4	3	3	--	4	2	2	2	--
B-7	Weather[d]				--	--	2	3	3	3	3	1	1	1	1	1	3	4	4	4	3.5	4	2	2	2	2.5

[a]Ratings of 1 indicate the least corroded, etc.

[b]Pi = pickled; Pa = passivated; Pr = pre-surfaced

[c]Skyward surfaces

[d]Earthward surfaces

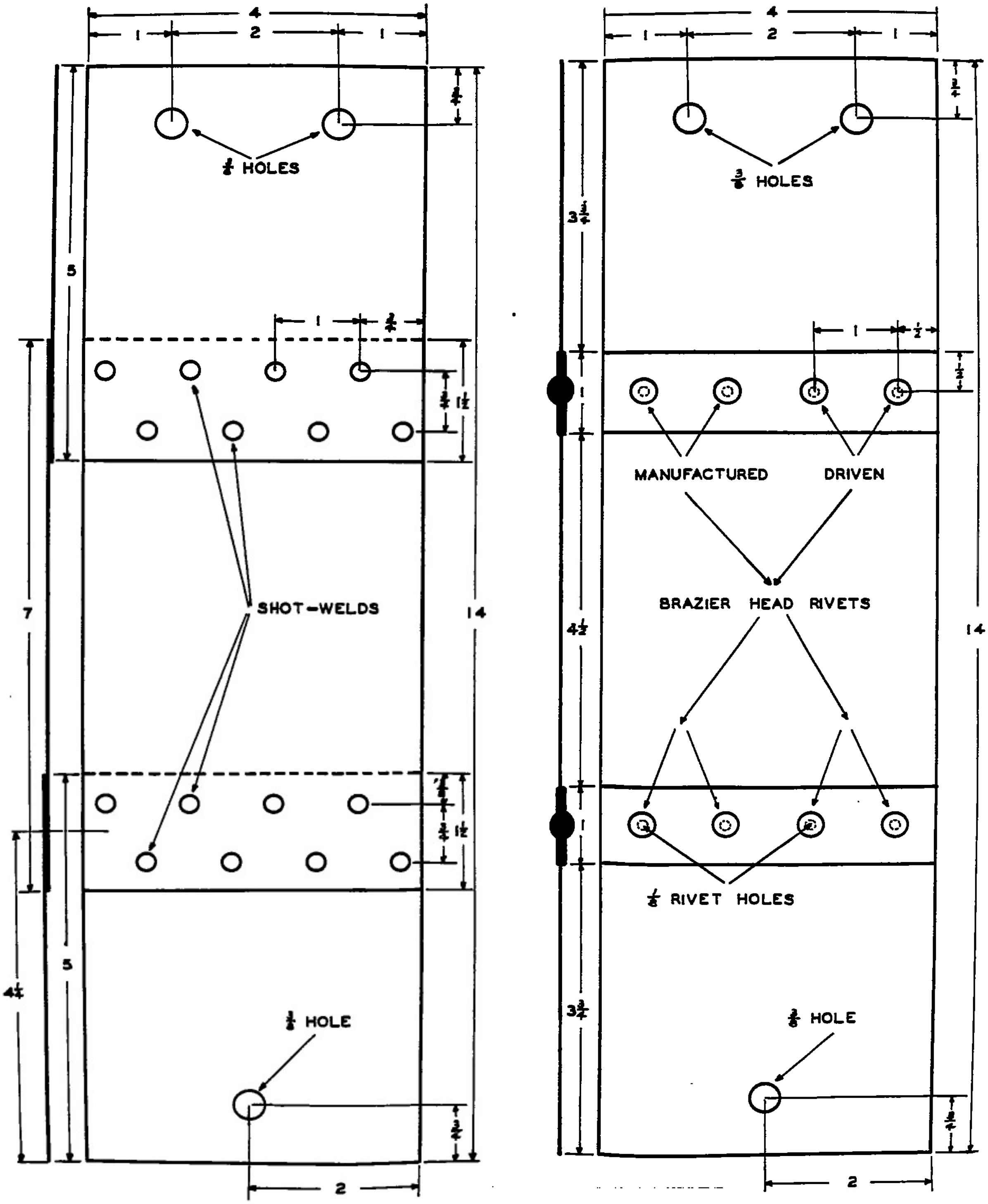


Figure 1.- Type of panels used for determining the corrosion of shot-welds, or of dissimilar metals.
All dimensions are in inches.

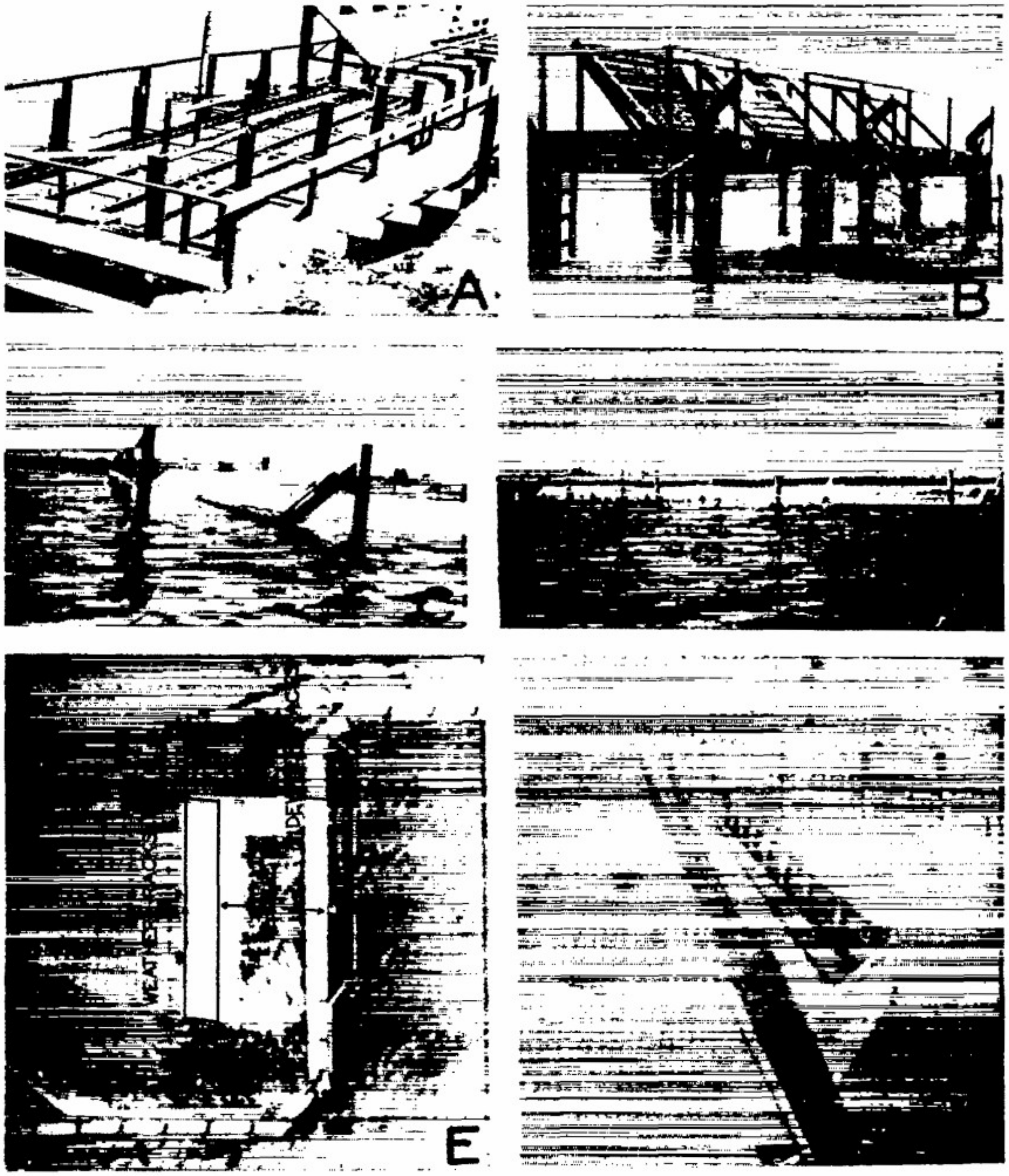
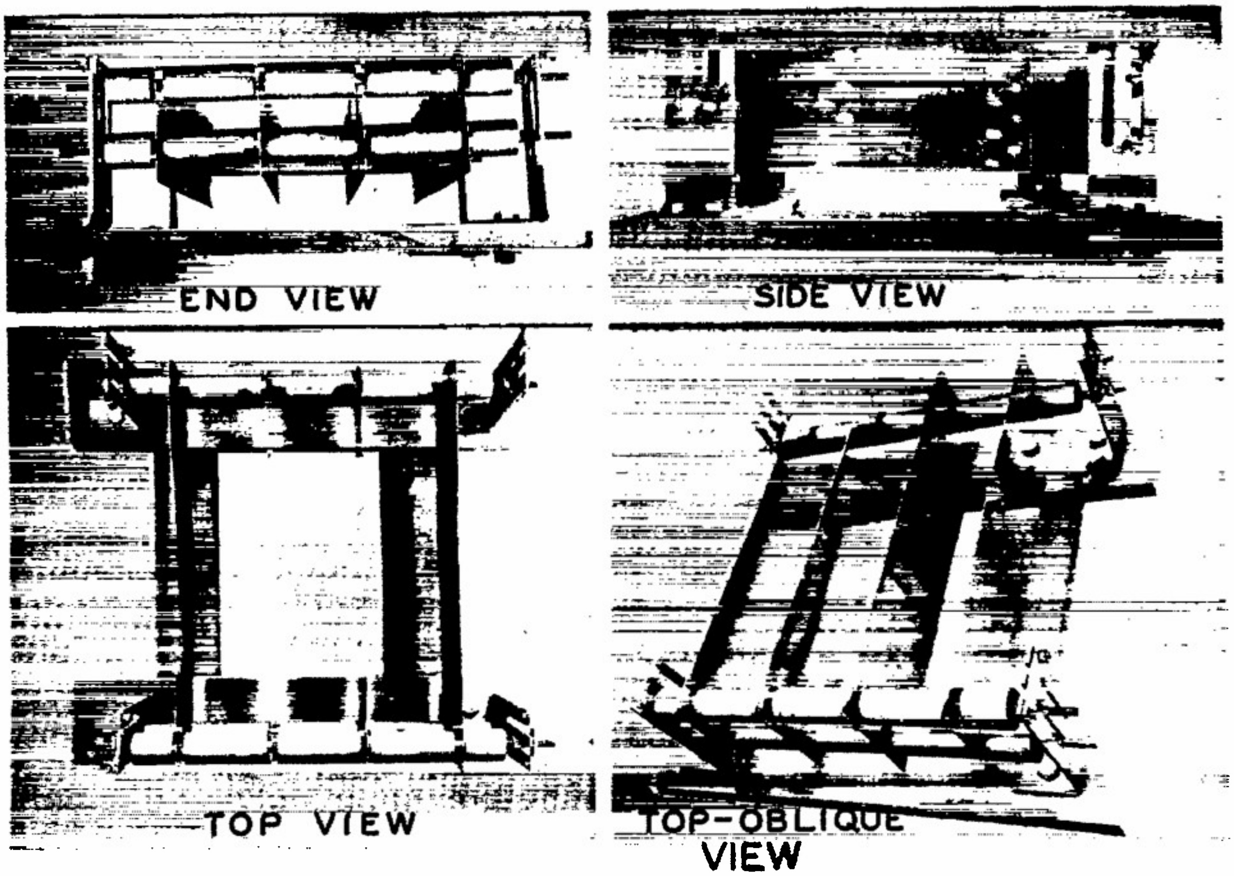


Figure 2.- The exposure racks used in the investigation. A, Weather and tidewater racks in Boush Creek, Hampton Roads, Va. B, Weather racks on Kure Beach, Cape Fear, N.C. C and D, Tidewater racks in Biscayne Bay, Chapman Field, Fla. E, Air view showing the relative location of the weather and tidewater racks in an artificial lagoon at Hampton Roads, Va. F, Tidewater racks of (E), viewed at closer range.



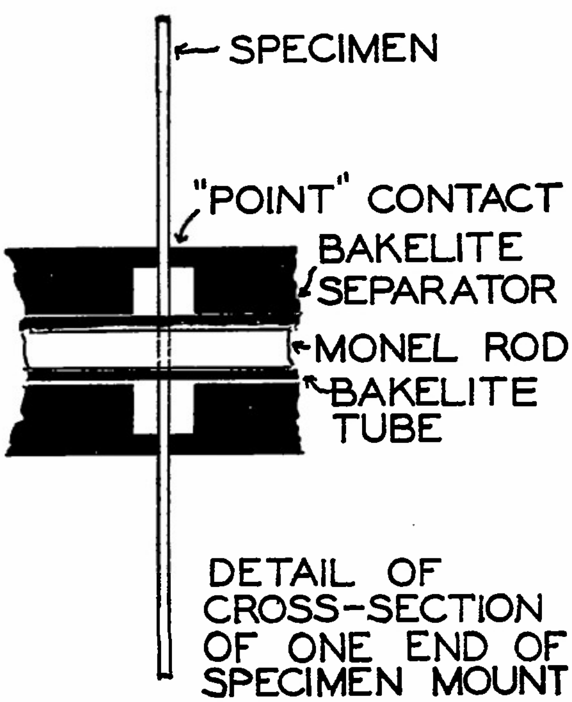


Figure 3.- Views of a model, and a sketch, showing details of the method used for suspending panels in the tidewater exposure racks at Hampton Roads, Va.

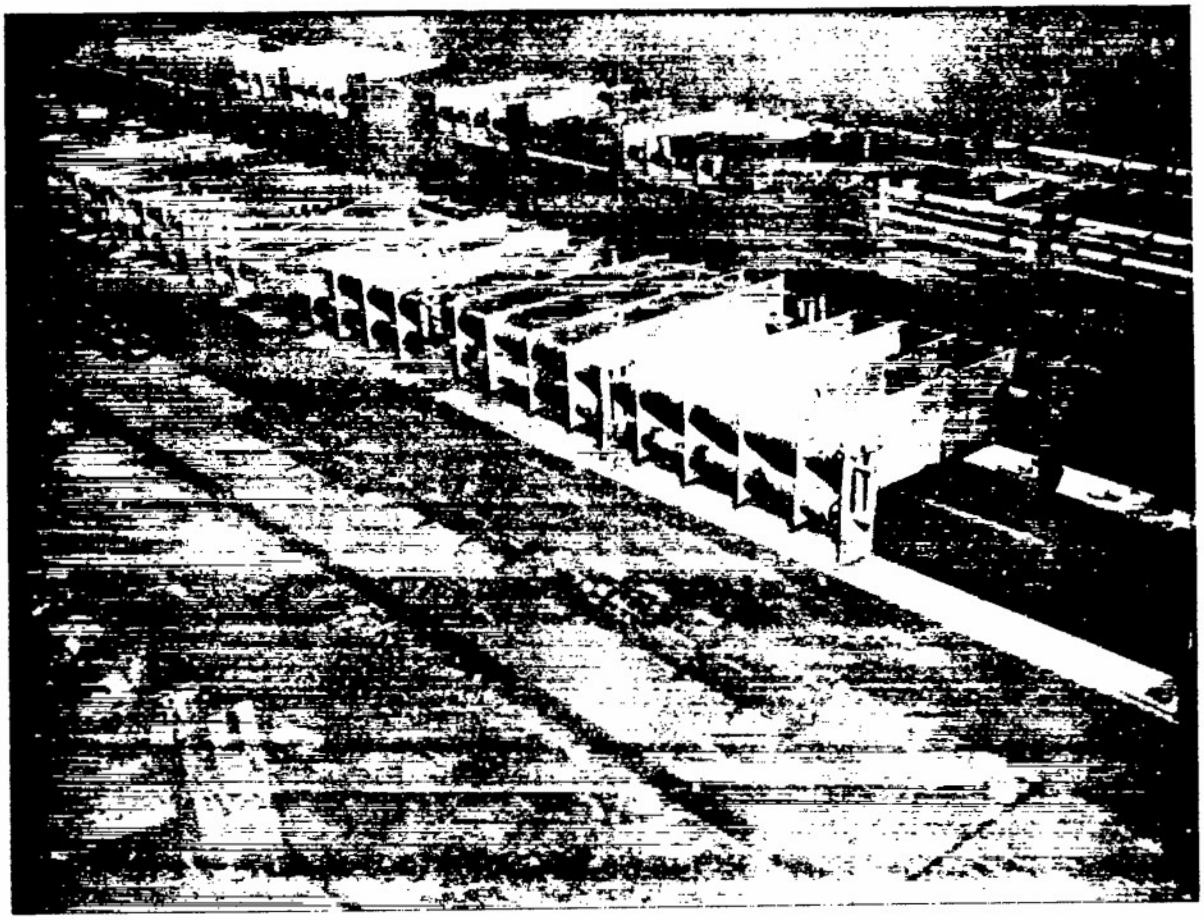


Figure 4.- Close-up view showing panels suspended in the tidewater racks at Hampton Roads, Va.

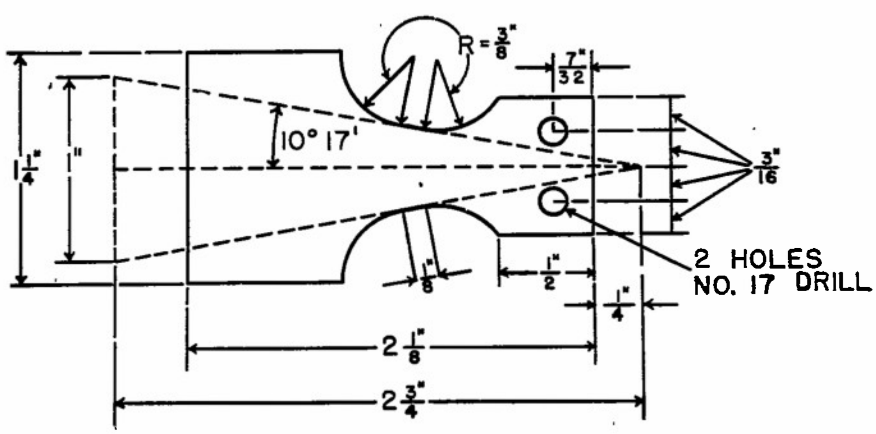


Figure 5.- The design and dimensions of the specimens for tests in the Krouse flexural fatigue machines.

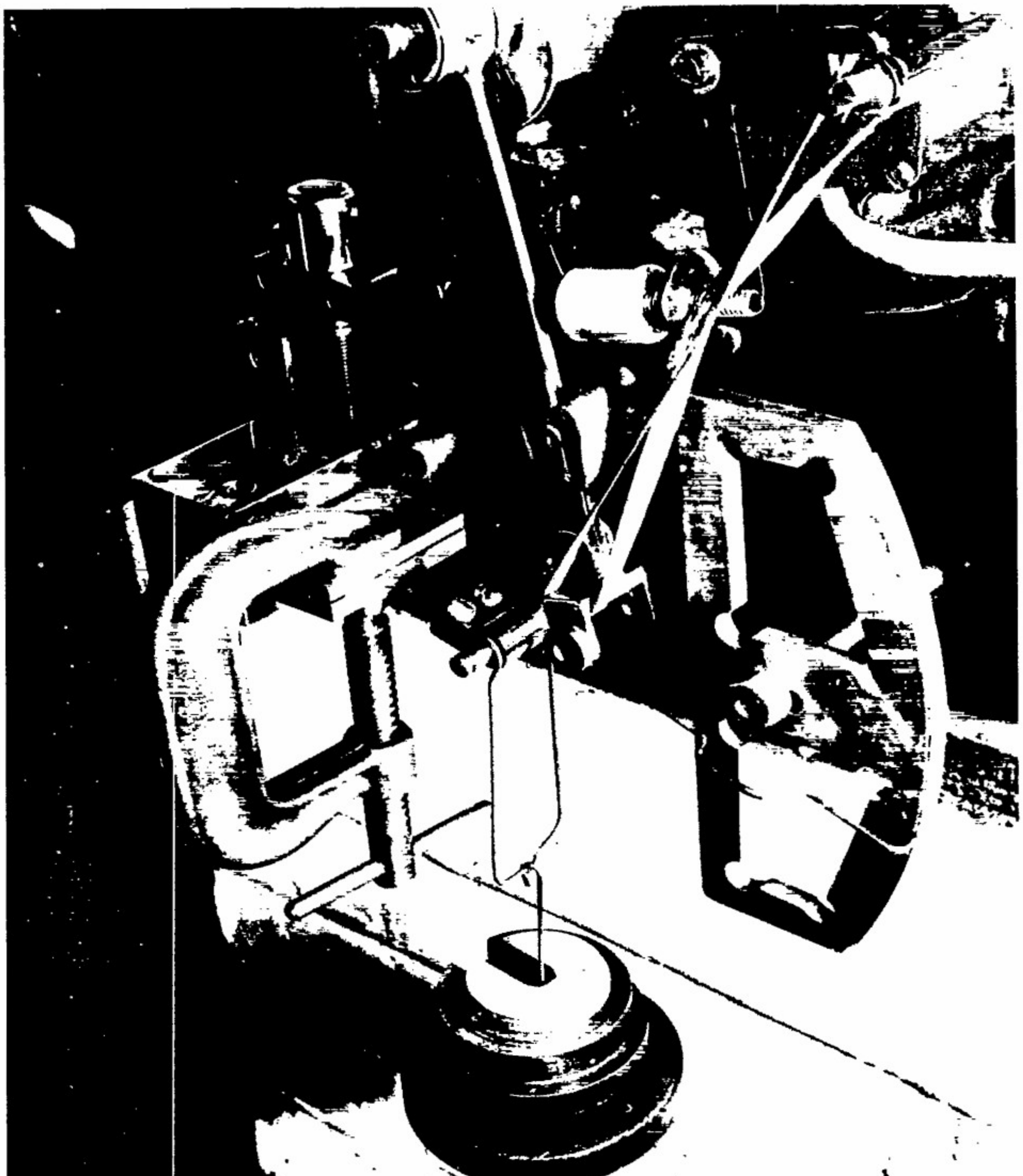


Figure 6.- A specimen loaded with dead weights for determining its deflection preparatory to calculating the maximum stresses. Deflection measurements were made by means of the pointer and scale on the arc at the right.

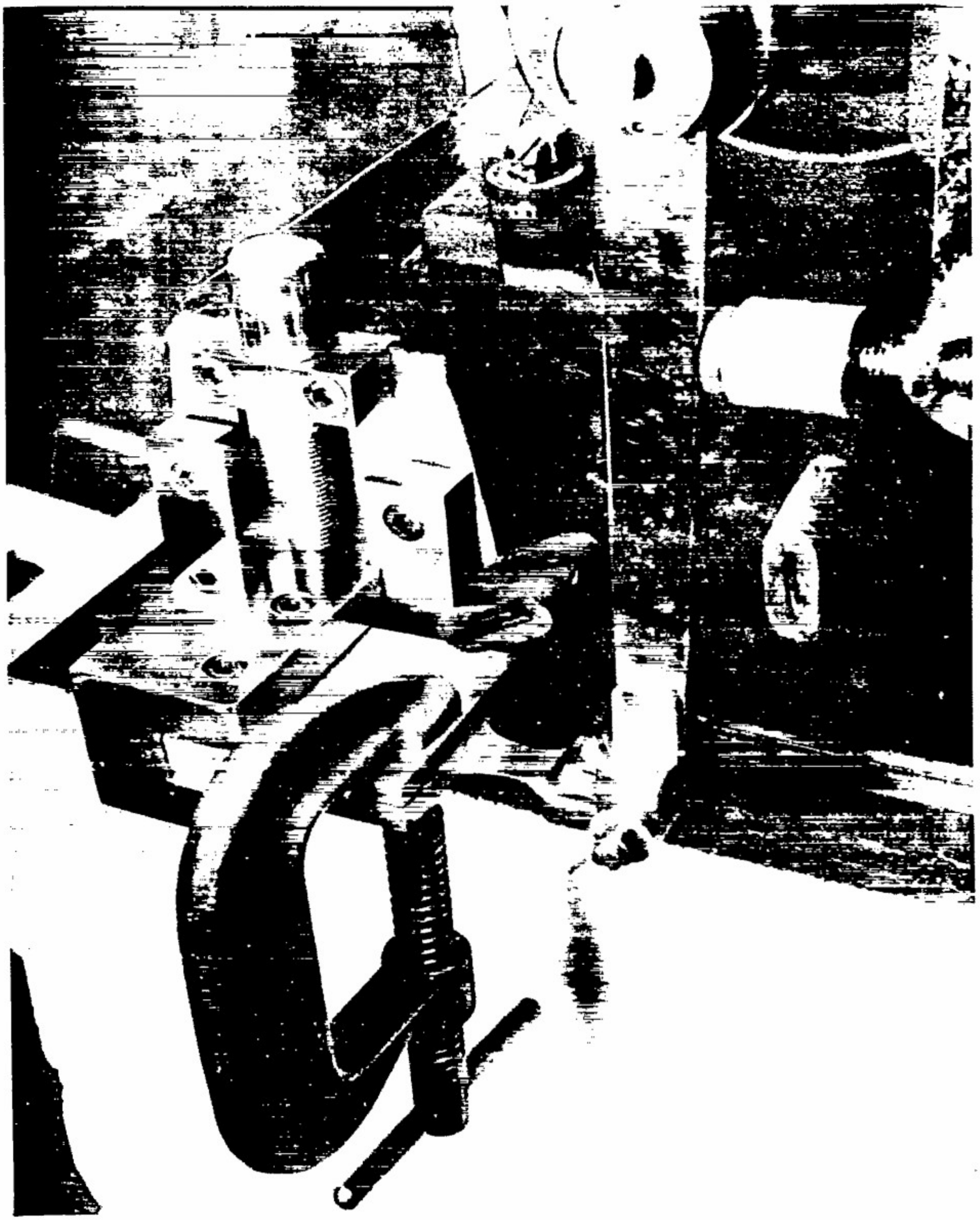


Figure 7.- A specimen in the Krouse flexural fatigue testing machine, showing the method of attaching it at the fixed and loading ends.

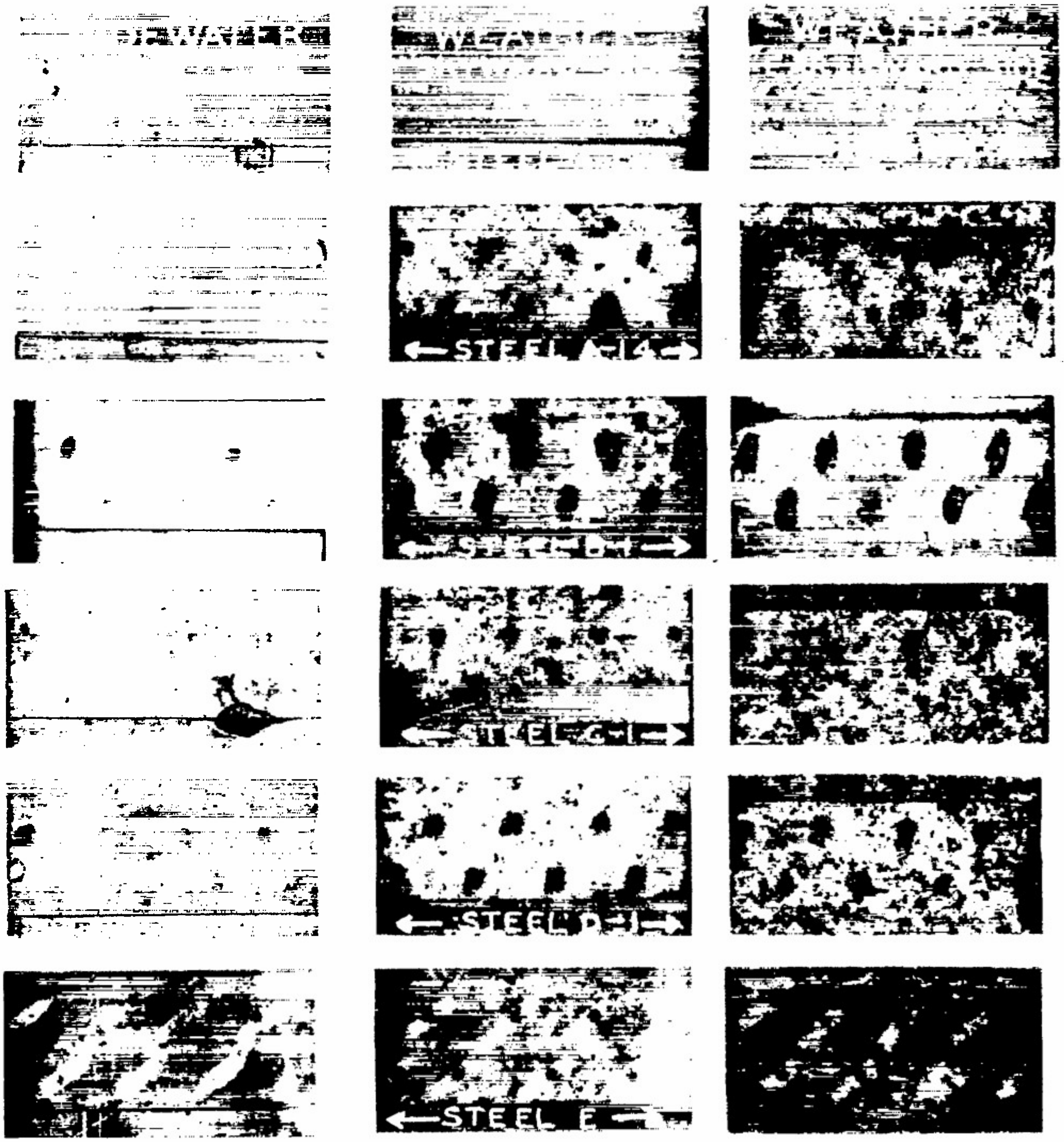


Figure 8.- Stainless steel panels, of various chemical compositions, exposed to the tidewater or weather at Hampton Roads, Va. for 36 months. Note that Steel B-1, containing 3.7 percent of molybdenum exhibited the least rust especially on the earthward surface, while Steel E, of the 16:1 type, showed the most rust. Steel A-1 was cleaned periodically, the others were not. x 1/2.

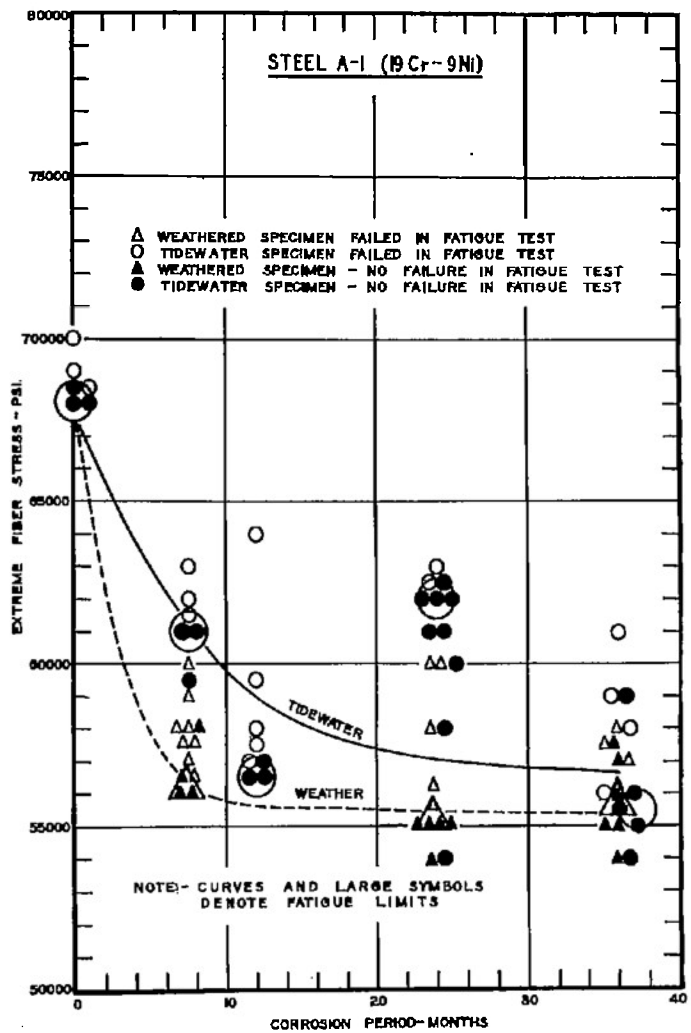


Figure 9.- Results of flexural fatigue tests on Steel A-1, giving the data for each specimen tested (small symbols), and the approximate fatigue limits (large symbols).

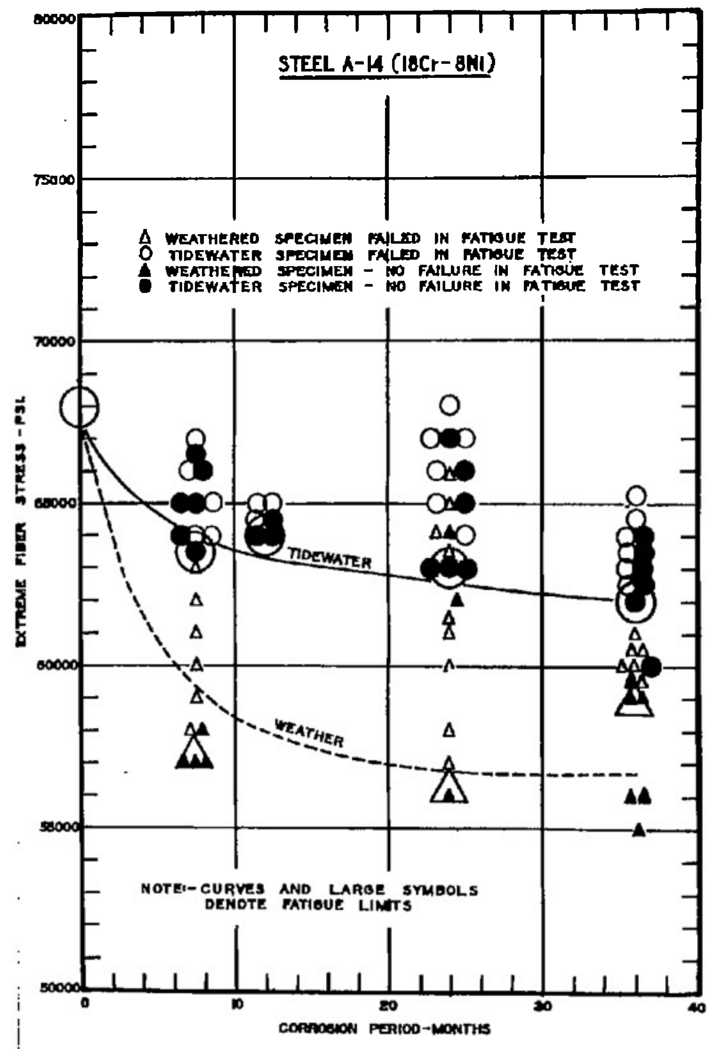


Figure 10.- Results of flexural fatigue tests on Steel A-14, giving the data for each specimen tested, and the approximate fatigue limits.

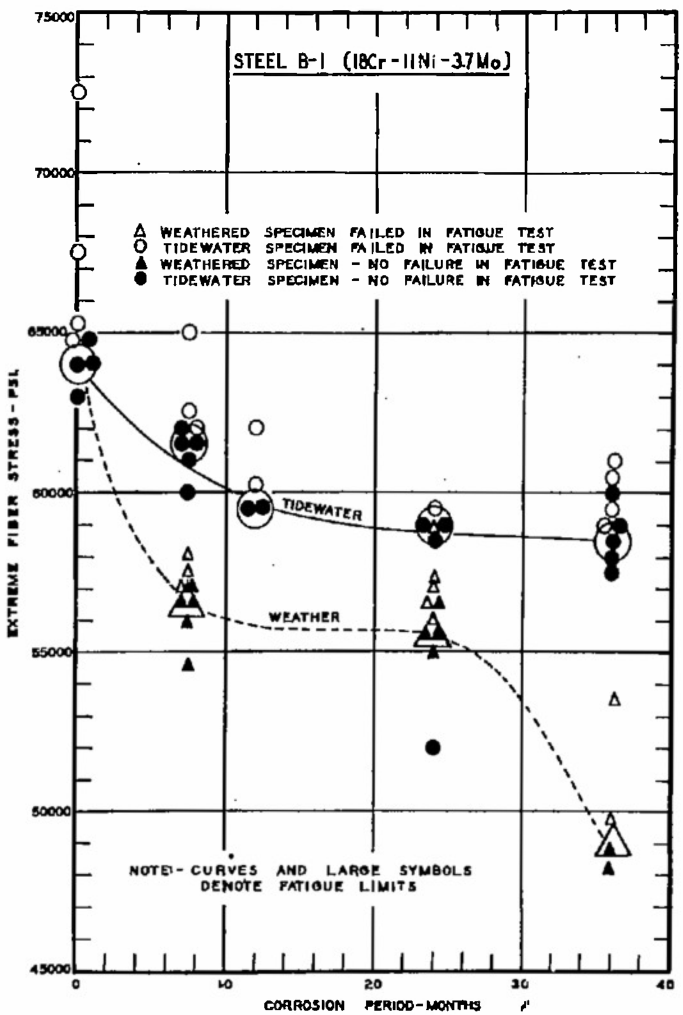


Figure 11.- Results of flexural fatigue tests on Steel B-1, giving the data for each specimen tested, and the approximate fatigue limits.

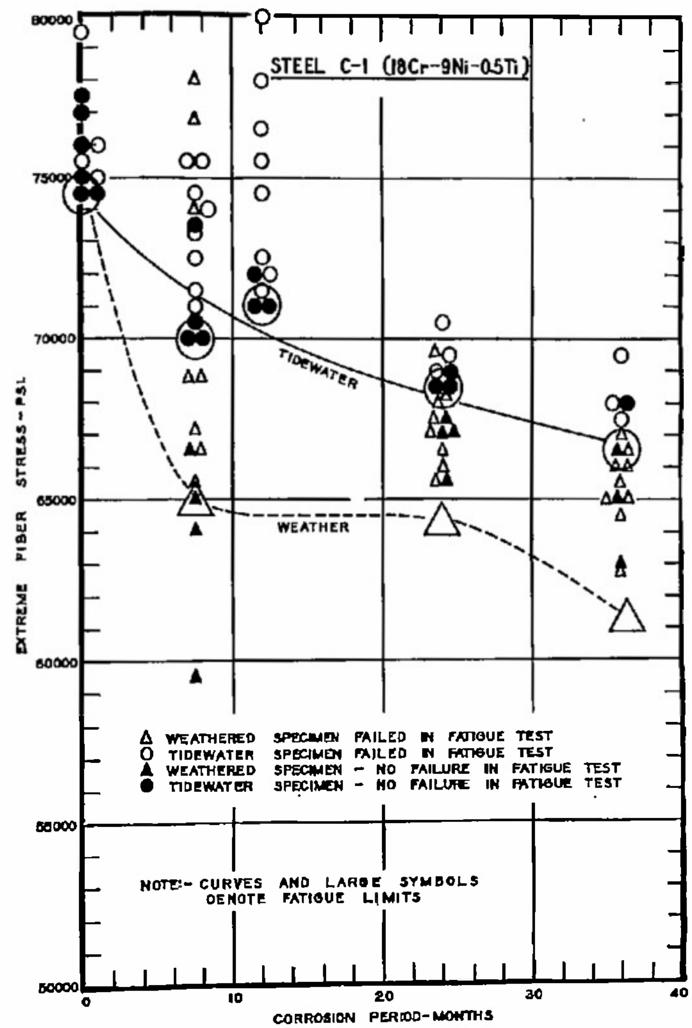


Figure 12.- Results of flexural fatigue tests on Steel C-1, giving the data for each specimen tested, and the approximate fatigue limits.

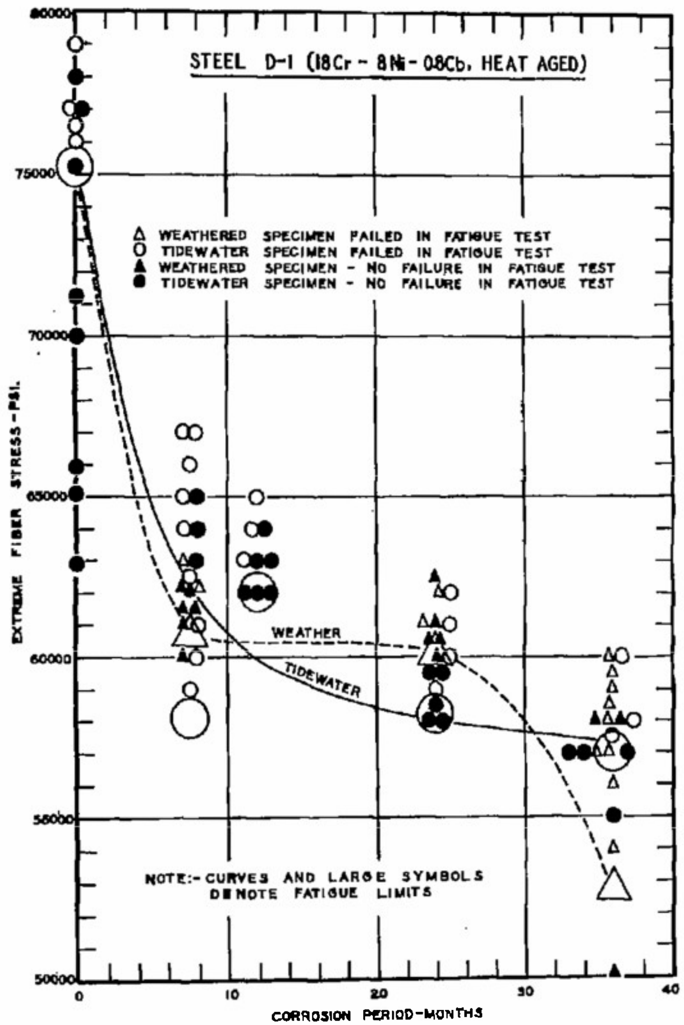


Figure 13.- Results of flexural fatigue tests on Steel D-1, giving the data for each specimen tested, and the approximate fatigue limits.

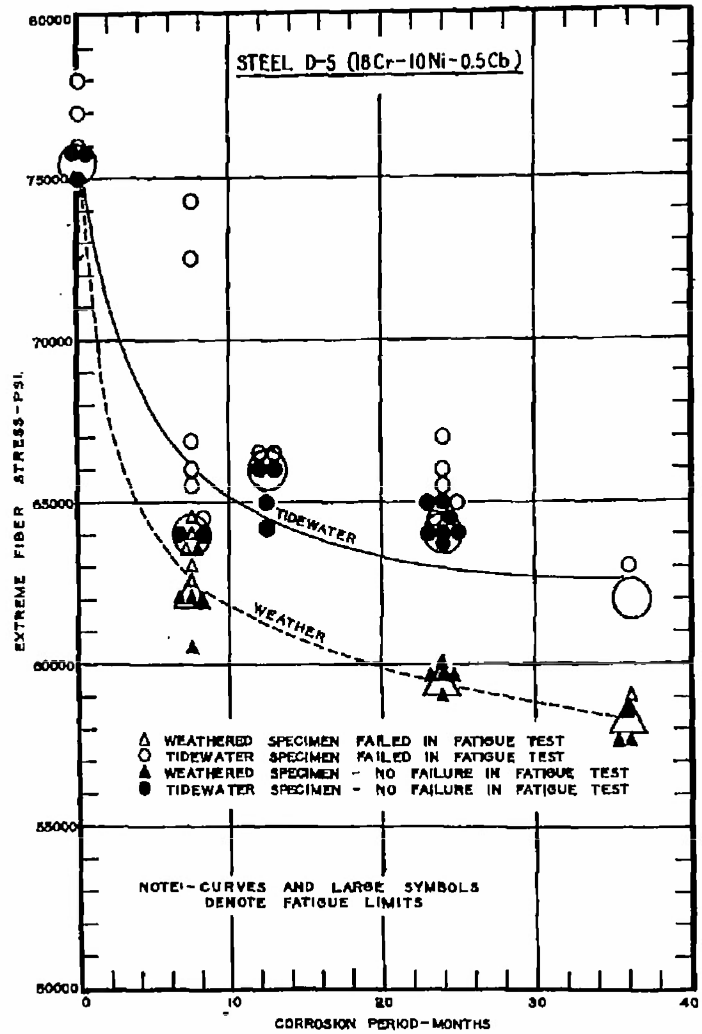
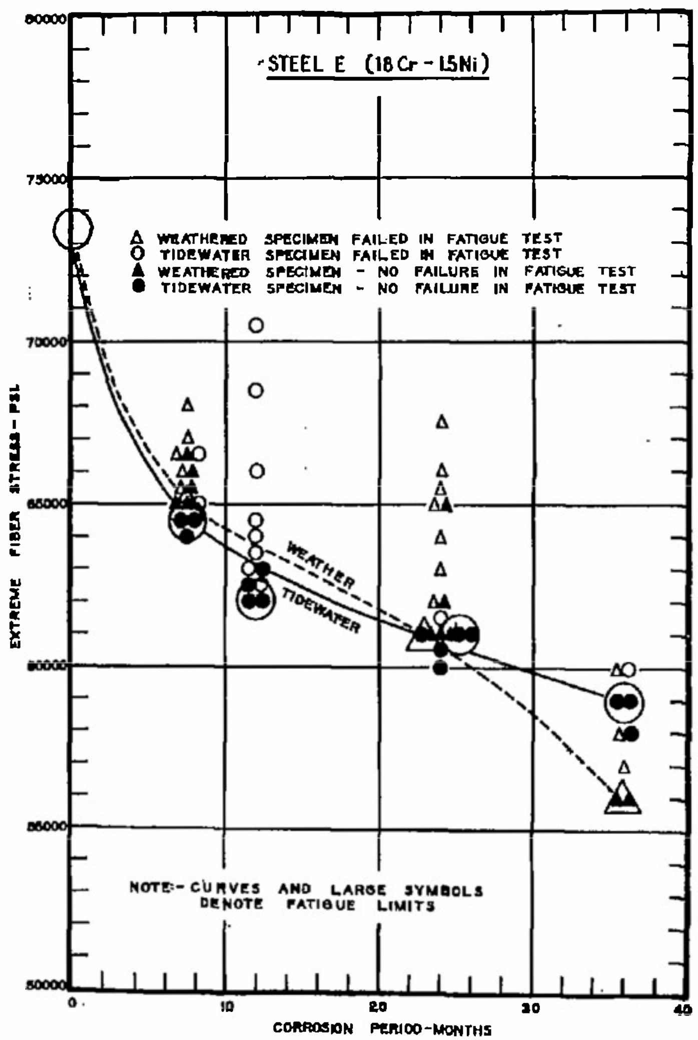


Figure 14.- Results of flexural fatigue tests on Steel D-5, giving the data for each specimen tested, and the approximate fatigue limits.



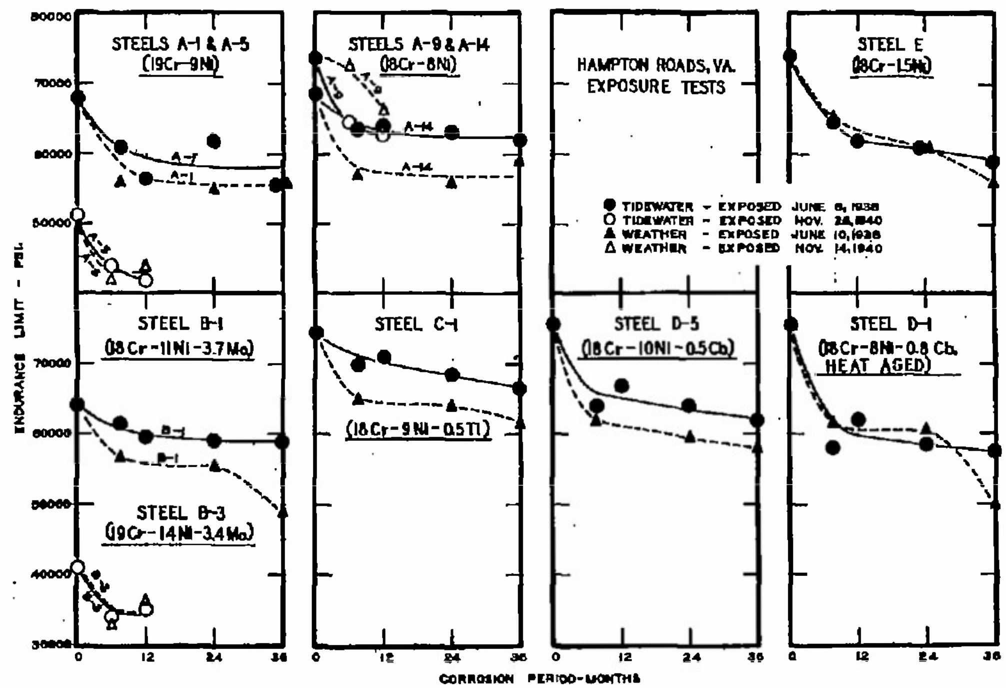


Figure 16.- The charts summarize the data for each of the steels (figs. 9-15, 19-21) exposed at Hampton Roads, Va., and show the loss in fatigue limits as related to the period of exposure. Panels exposed in 1938 were located at Boush Creek, while those exposed in 1940 were located at the Lagoon.

Figure 15.- Results of flexural fatigue tests on Steel E, giving the data for each specimen tested, and the approximate fatigue limits.

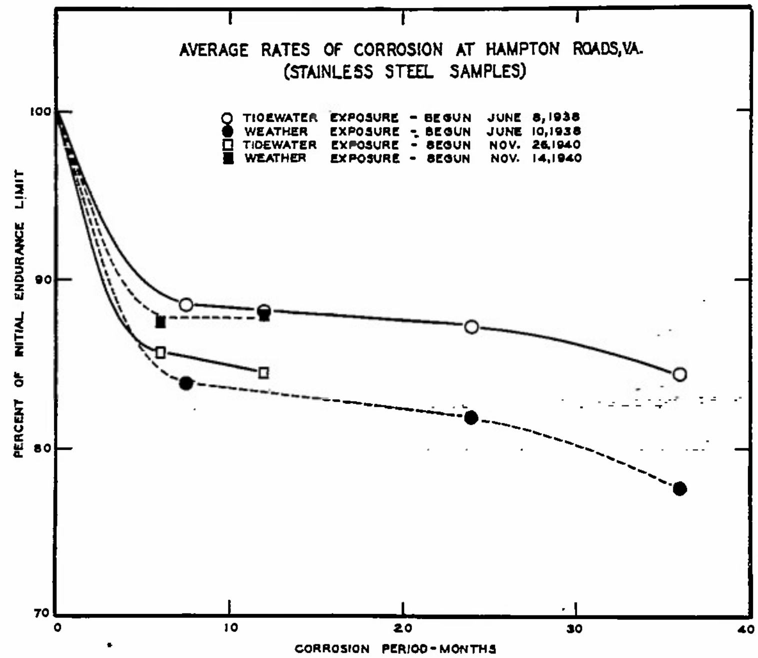


Figure 17.- Panels exposed in 1938 were located at the Boush Creek site, while those exposed in 1940 were located at the Lagoon, at the U.S. Naval Air Station, Hampton Roads, Va. The data are the average for all the stainless steel panels, irrespective of their chemical compositions.

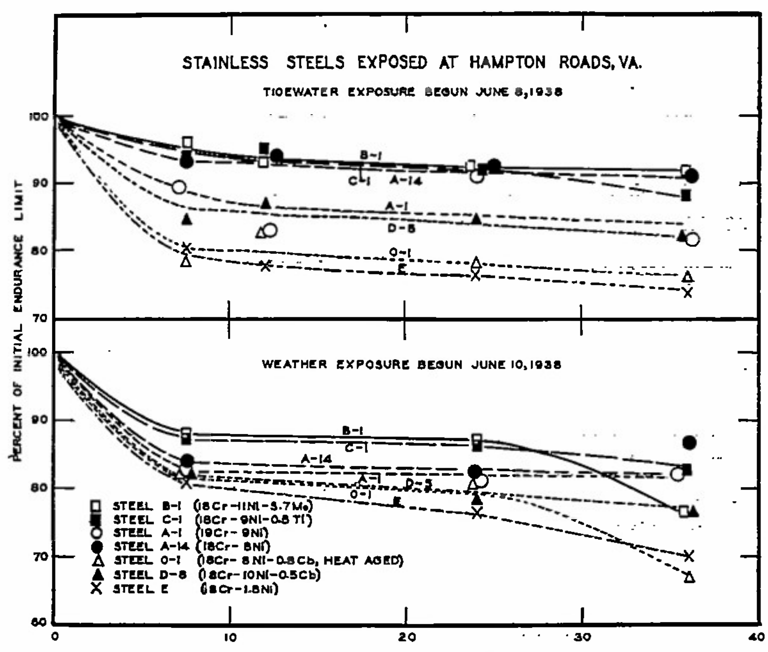


Figure 18.- The comparative rates of corrosion for each steel exposed at the Boush Creek site, Hampton Roads, Va.

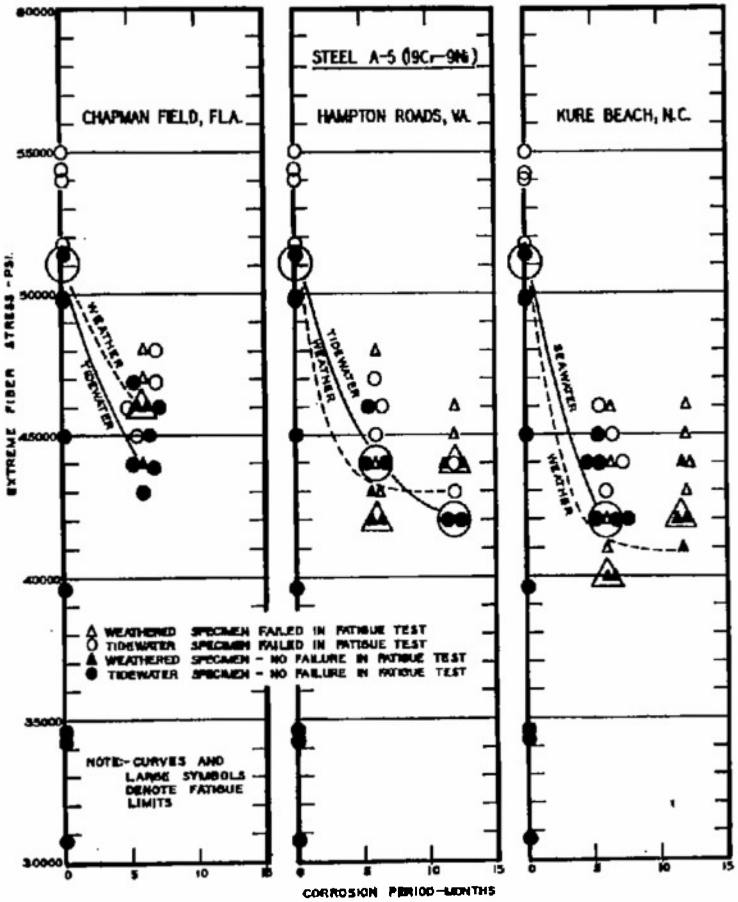


Figure 19.- Results of flexural fatigue tests on Steel A-5 exposed simultaneously at the three localities, giving the data for each specimen tested, and the approximate fatigue limits.

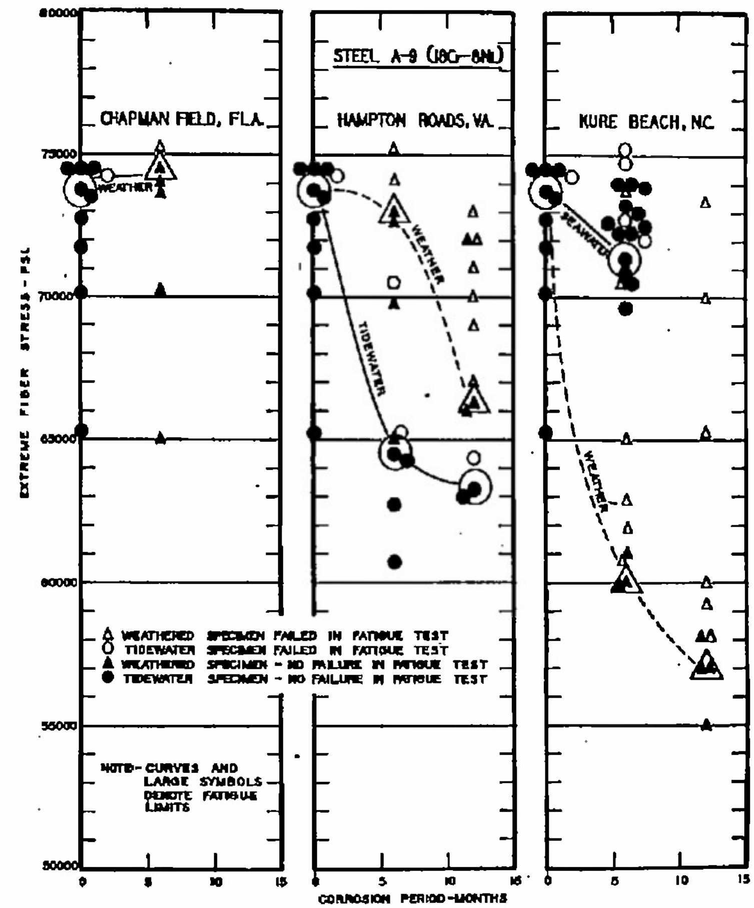


Figure 20.- Results of flexural fatigue tests on Steel A-9 exposed simultaneously at the three localities, giving the data for each specimen tested, and the approximate fatigue limits.

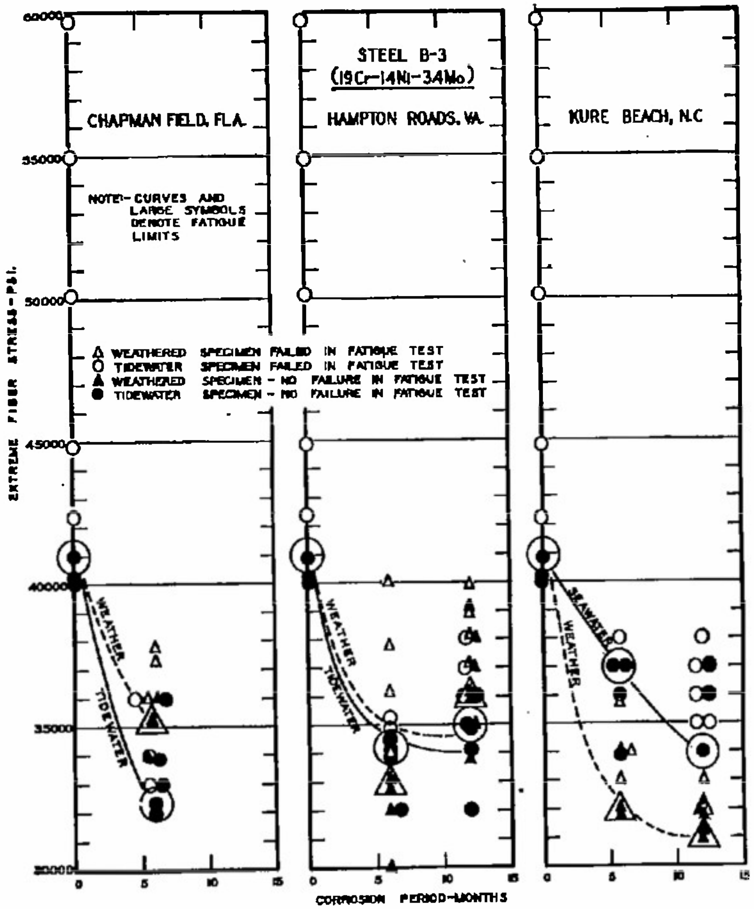


Figure 21.- Results of flexural fatigue tests on Steel B-3 exposed simultaneously at the three localities, giving the data for each specimen tested, and the approximate fatigue limits.

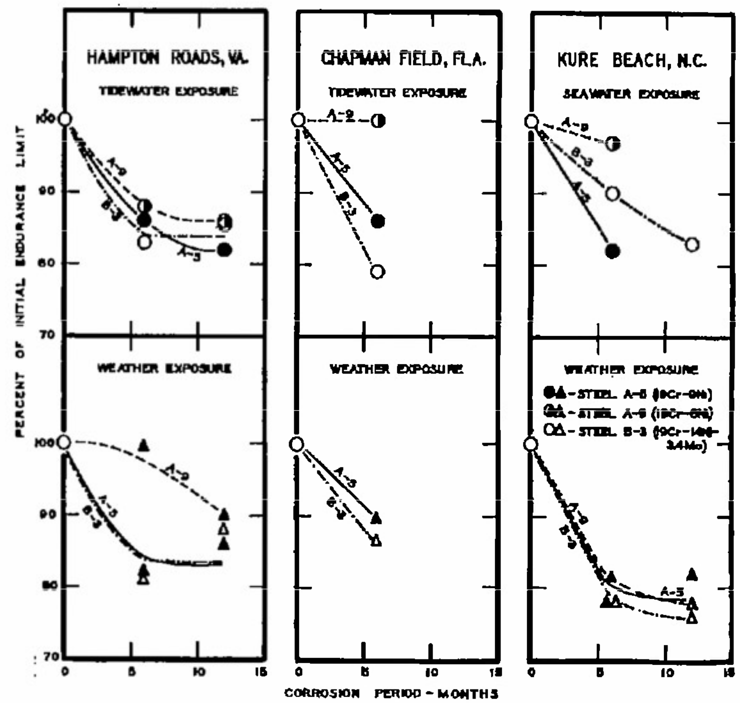


Figure 22.- The charts summarize the data for each of the steels exposed simultaneously at the three localities (figs. 19, 20 and 21), and show the loss in fatigue limits as related to the period and type of exposure.

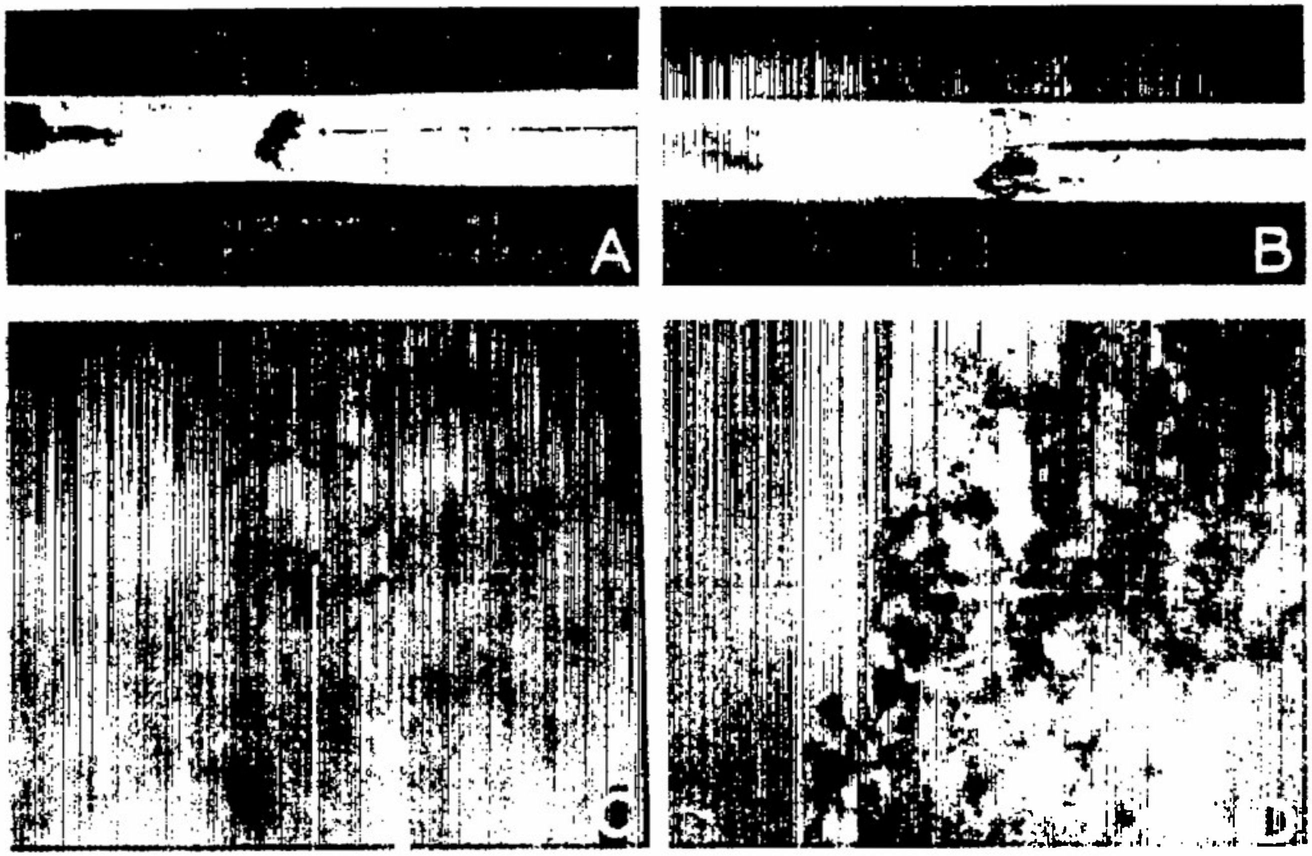


Figure 23.- Corrosion on shot-welds exposed to a boiling solution of mixed chlorides in laboratory tests. A, Pits in Steel C-1 (titanium-bearing) on a welded cross-section exposed for 15 days. x 10; B, Steel D-5 (columbium-bearing), exposed under the same conditions as in "A". x 10; C, Pin-hole on Steel C-1 shot-weld, which developed in 100 days. x 9; D, Corrosion at the edge of a shot-weld on Steel C-1 after 120 days. x 9.

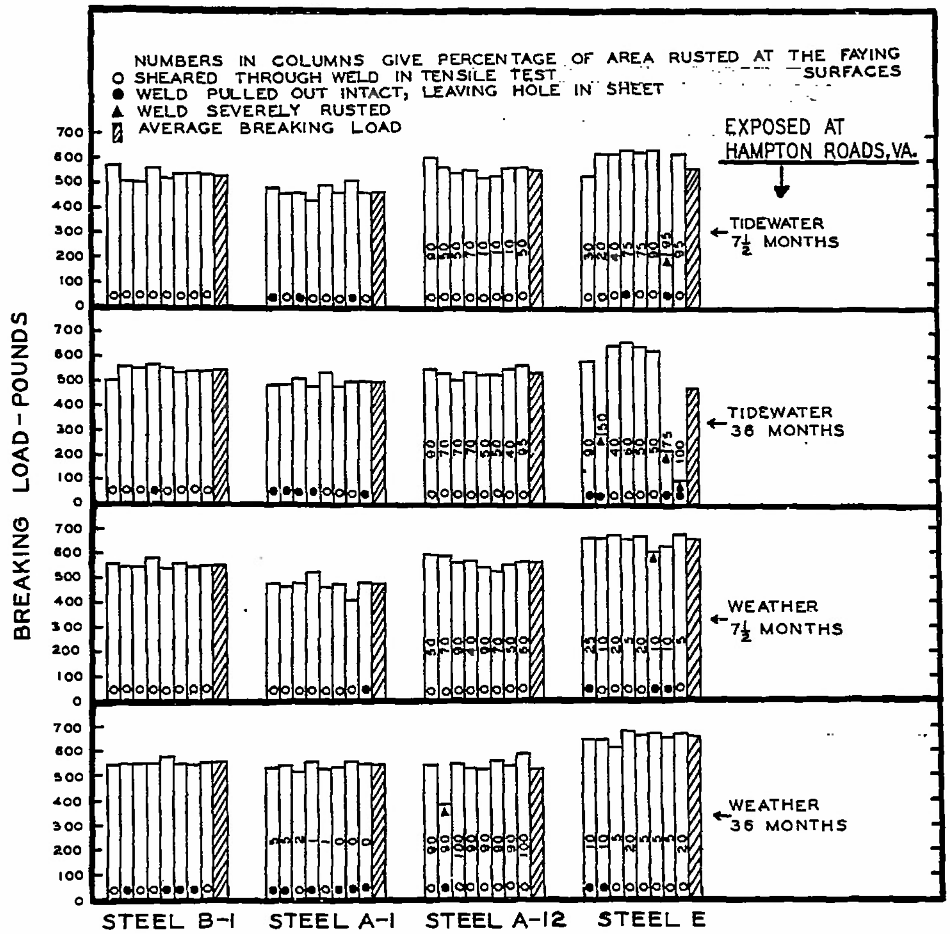


Figure 24.- Results of tensile tests on individual shot-welds from representative panels after exposure at Hampton Roads, Va.

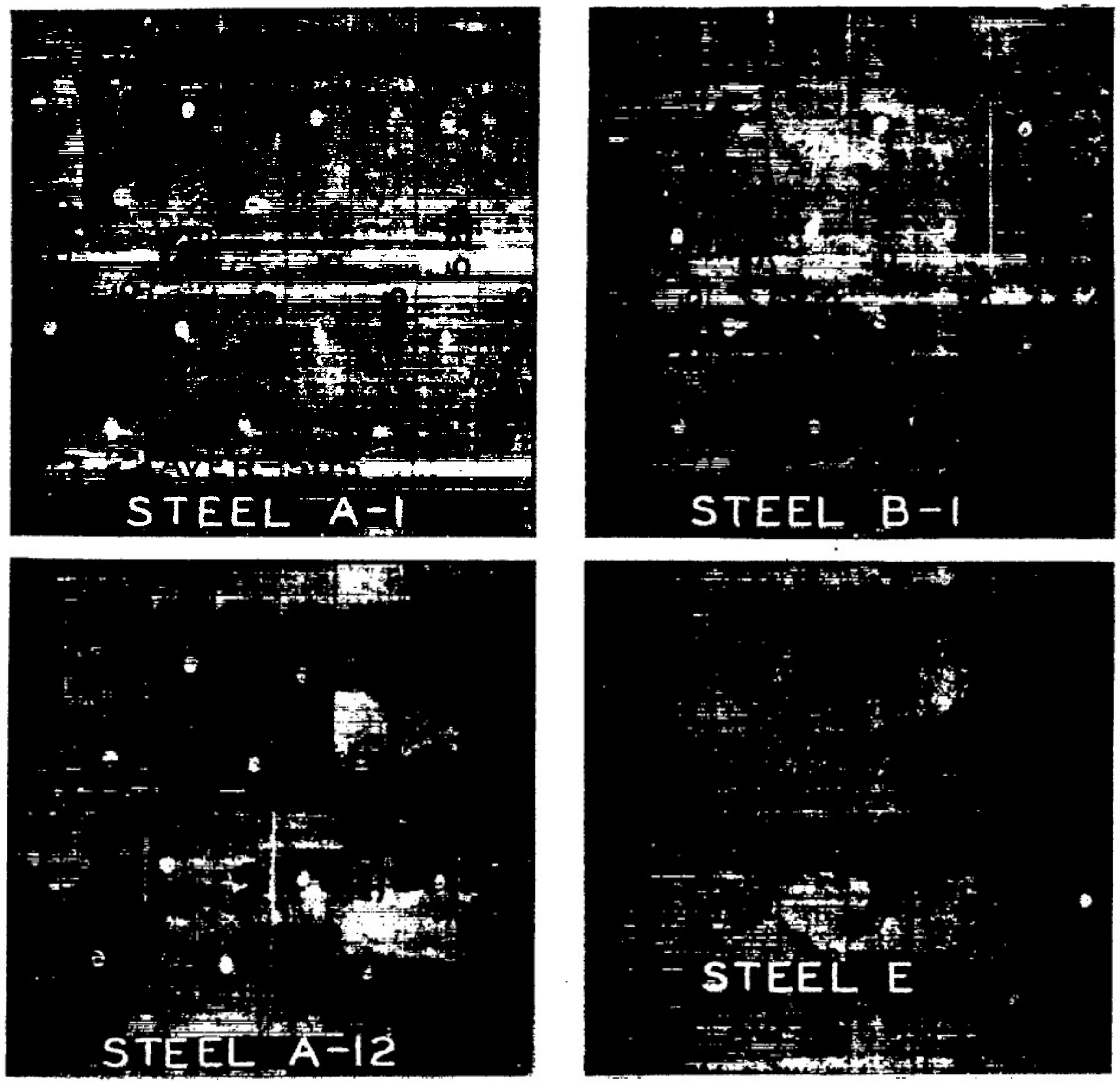


Figure 25.- The faying surfaces of representative shot-welded panels exposed to tidewater at Hampton Roads, Va. for three years shown after tensile tests were made. The breaking load for each weld is indicated on the photograph. Note the lack of rust on samples having a grease at the faying surfaces prior to shot-welding (Steels A-1 and B-1). x 3/4

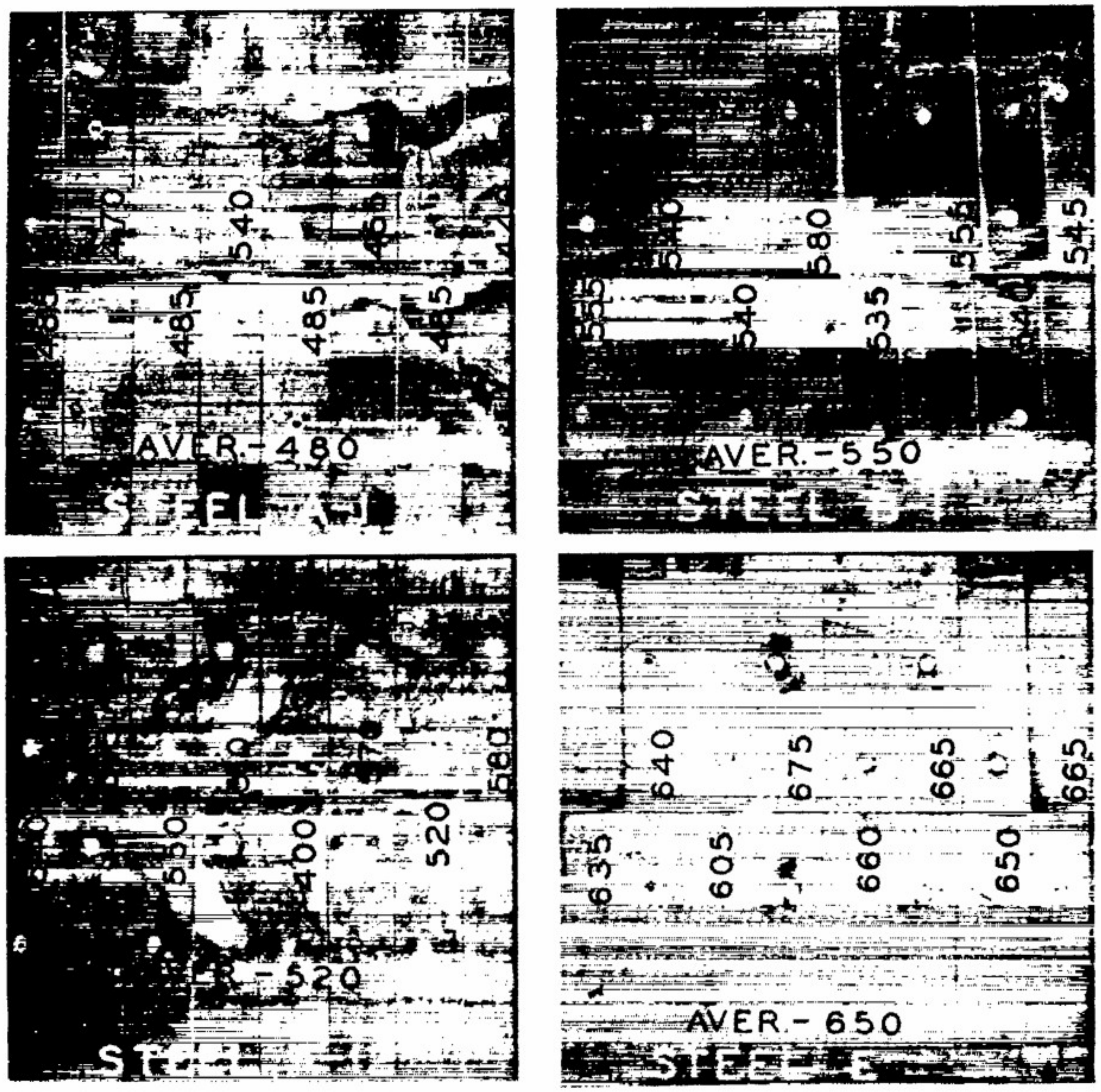


Figure 26.- The faying surfaces of panels, comparable to those shown in figure 25, but exposed to the weather for three years at Hampton Roads, Va. Surfaces to which no grease was applied prior to welding (Steel A-12) exhibit considerable rust. x 3/4.

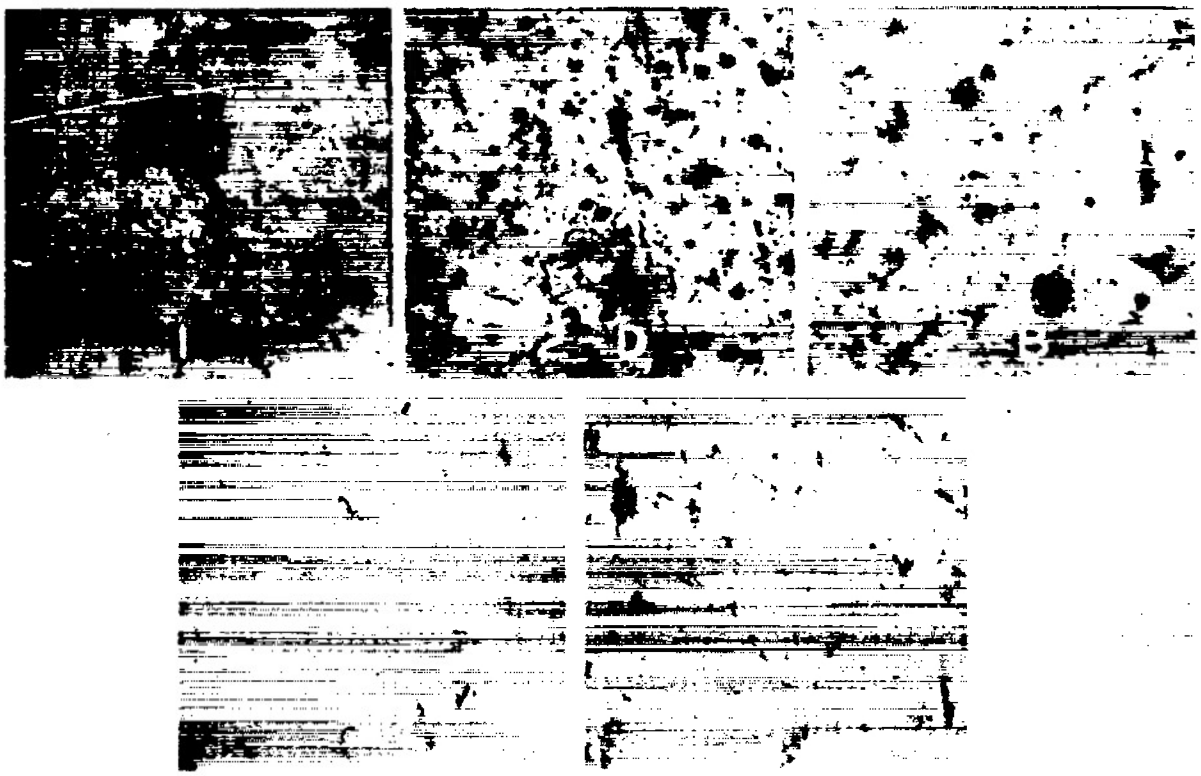


Figure 27.- Earthward surfaces of panels with different commercial surface finishes, after exposure to the weather at Hampton Roads, Va. for six months. Note the decrease in quantity and thickness of the corrosion products, as the degree of surface finish is improved. x1.

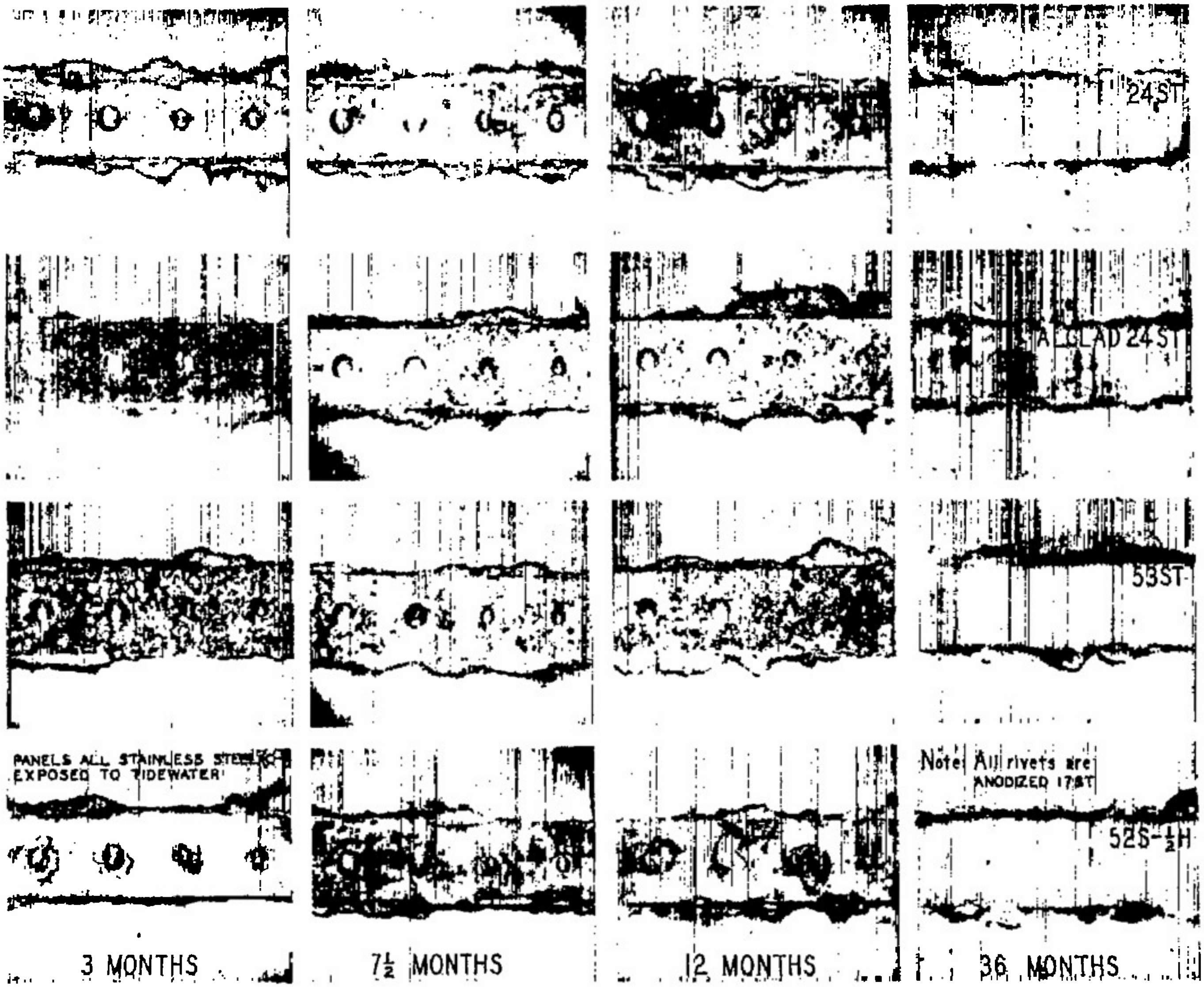


Figure 28.- Strips of aluminum alloys, coupled in a 1:7 area ratio on panels of stainless steel, and exposed to the tidewater at Hampton Roads, Va. for the periods indicated. Note the severe corrosion on the strips and the quantities of corrosion products accumulated at the edges of juncture. x 1/2.

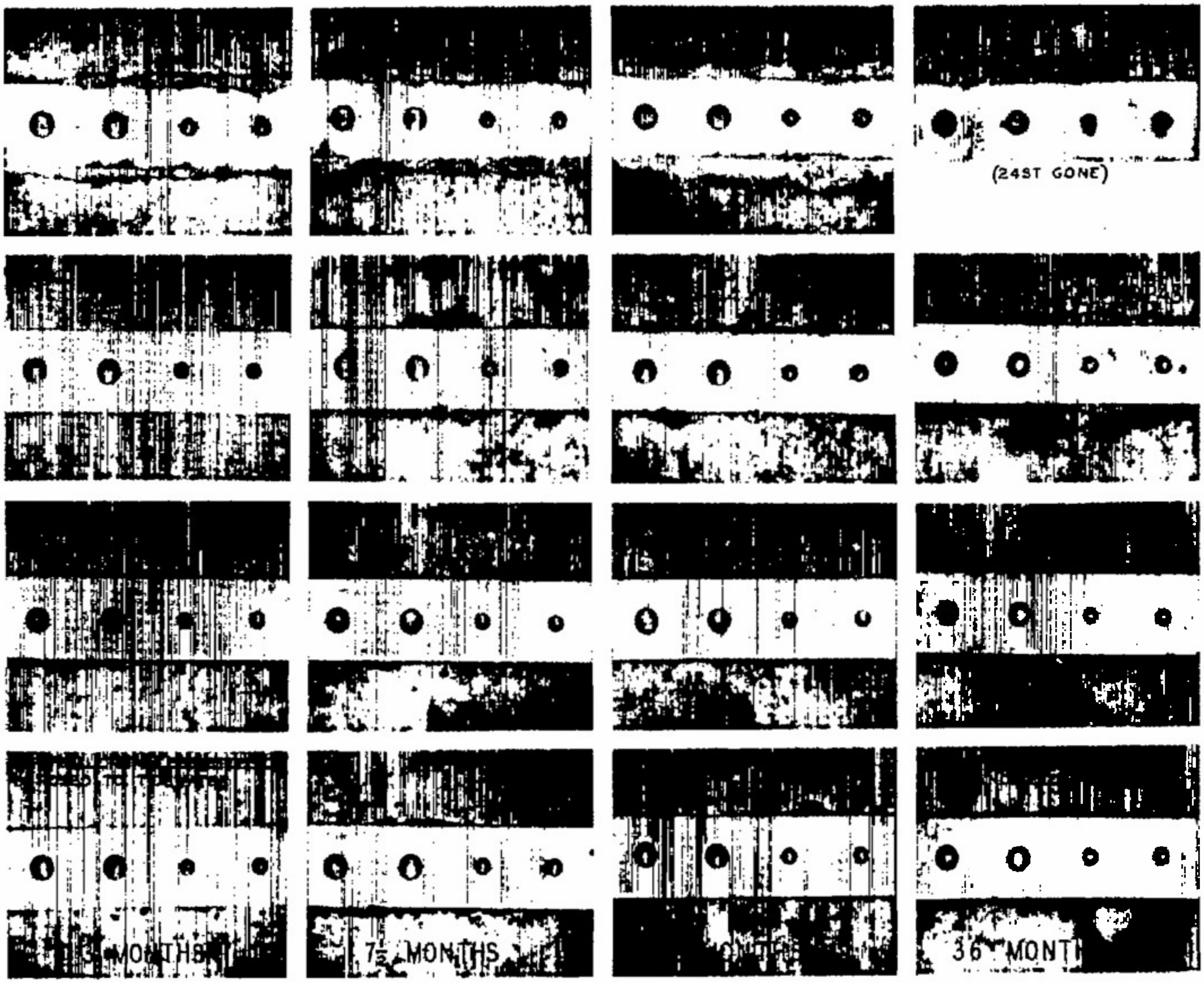


Figure 29.- Strips of stainless steel, coupled in a 1:7 area ratio with panels of aluminum alloys, and exposed to the tidewater at Hampton Roads, Va. for the periods indicated. Note that the aluminum alloys are less severely attacked, and the quantities of corrosion products at the edges of juncture are less than in figure 28. x 1/2.

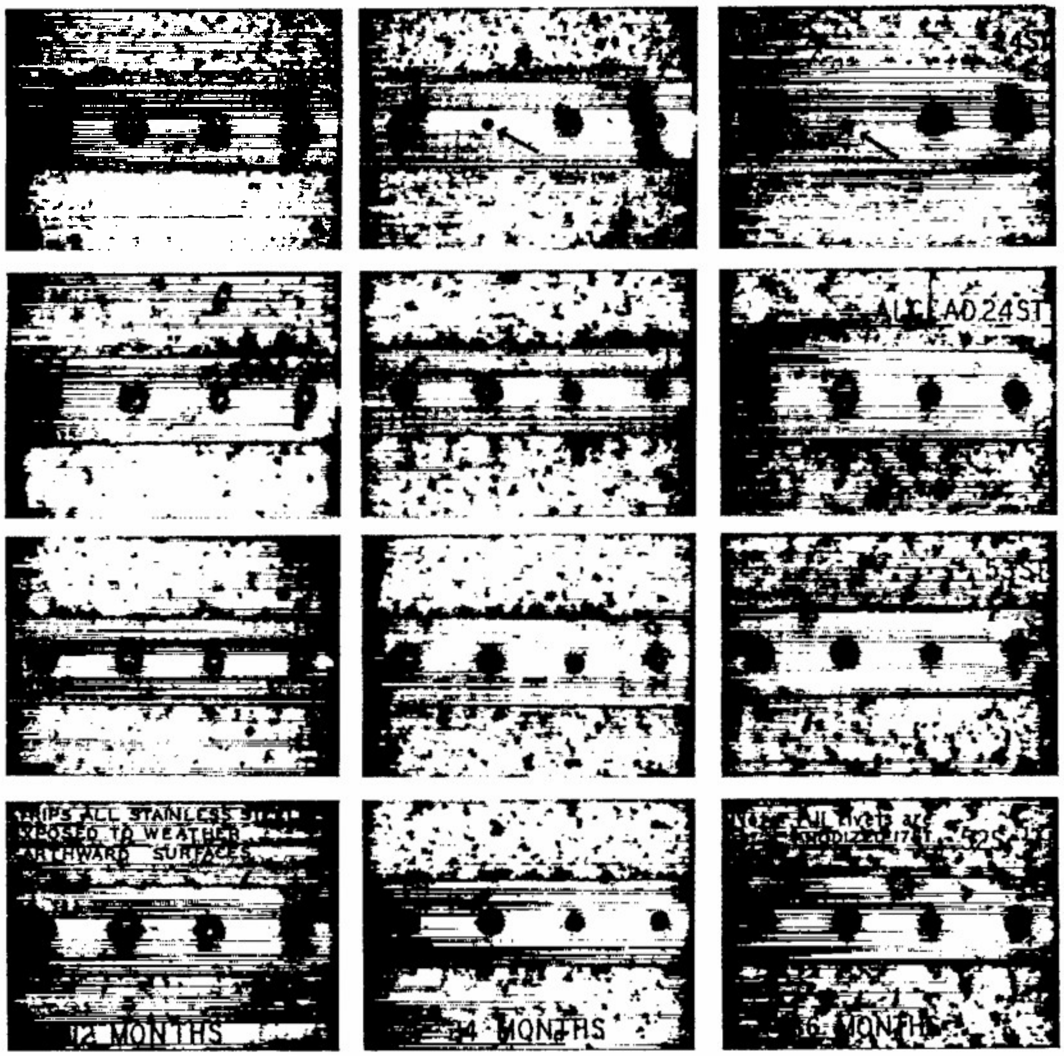


Figure 30.- Earthward surfaces of strips of stainless steel coupled in a 1:7 area ratio with panels of aluminum alloys, and exposed to the weather at Hampton Roads, Va. for the periods indicated. Note that two rivet heads, joining the steel to alloy 24ST (arrows), have broken off because of the stresses imposed by the corrosion products at the faying surfaces. x 1/2.

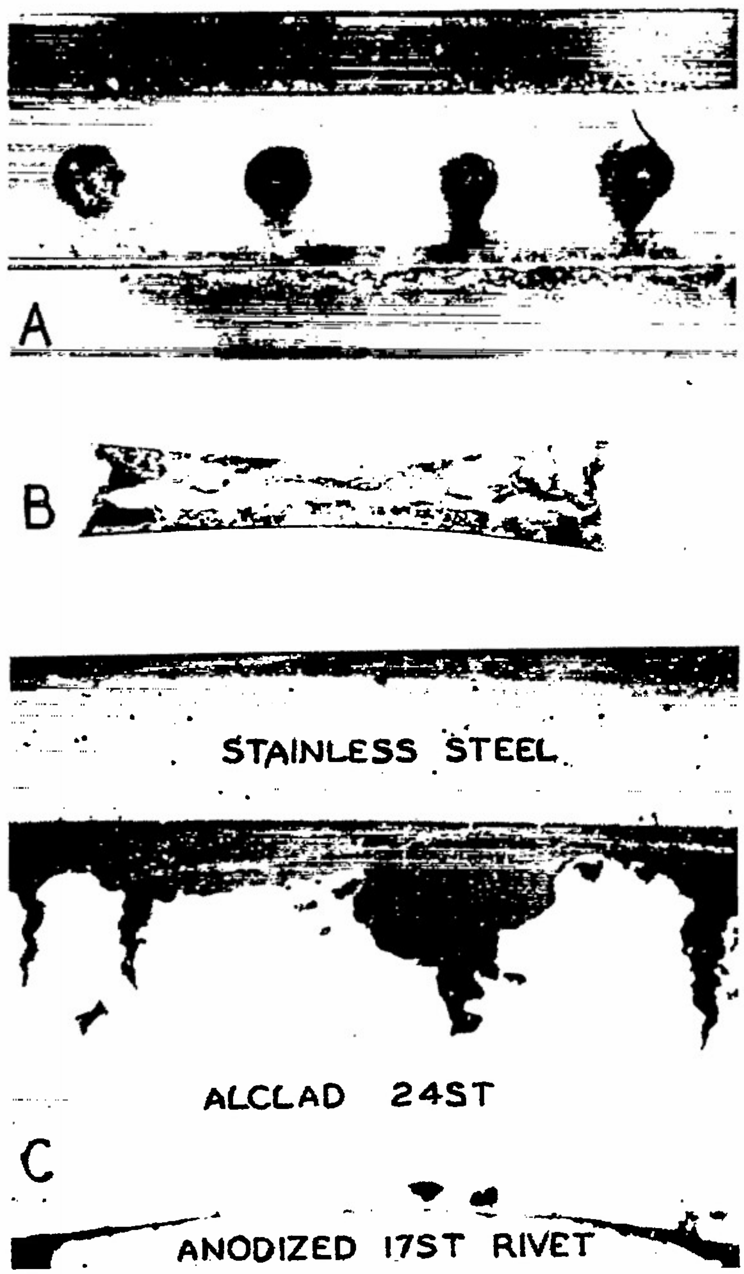


Figure 31.- Examples of stress corrosion on panels having stainless steel coupled with light metal alloys. A, Crack on stainless steel strip joined to a magnesium alloy panel, Dowmetal M. Exposed two years to the weather, earthward surface. x 1. B, Cross-section showing the large amount of corrosion products at the faying surfaces of (A). x 2-1/2. C, Cracks in Alclad 24ST strip attached to a stainless steel panel, exposed to tidewater for two years. x 50.

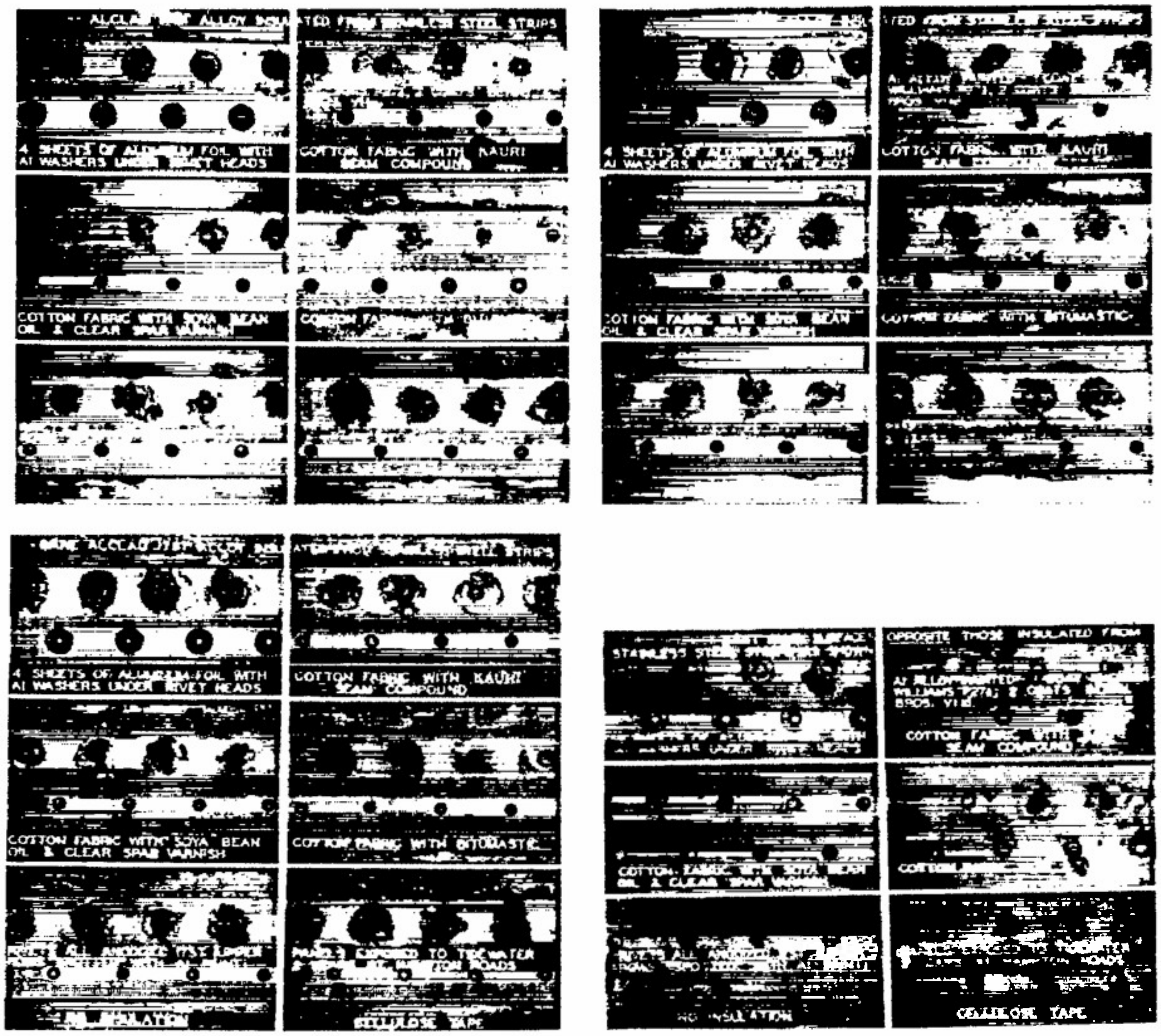


Figure 32.- Panels of aluminum alloys joined to stainless steel strips and exposed to tidewater at Hampton Roads, Va. for two years with the various insulators between the strips and the panels. The upper rows of rivet heads were painted with an aluminum pigmented varnish. Note the absence of corrosion products along the edges of the strips insulated by aluminum foil. x 2/5.

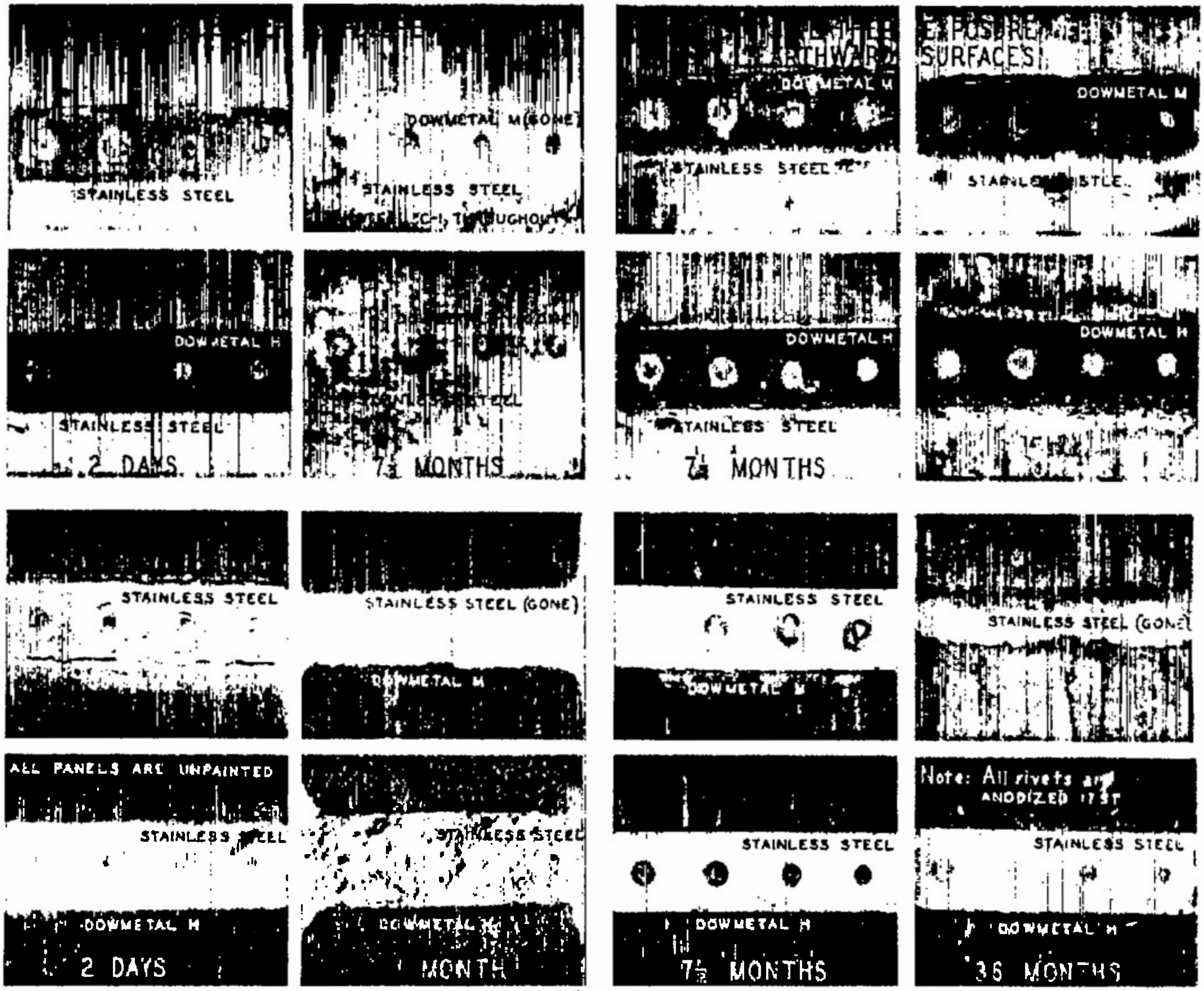


Figure 33.- Unpainted panels exposed at Hampton Roads, Va., for the periods indicated, having stainless steel and magnesium alloys in contact with each other. Note the electrolytic deposition of white corrosion products on the uncorroded steel, on panels exposed to the tidewater. The upper quadrants show Dowmetal strips on steel; the lower quadrants show the reverse arrangement. x 1/2.

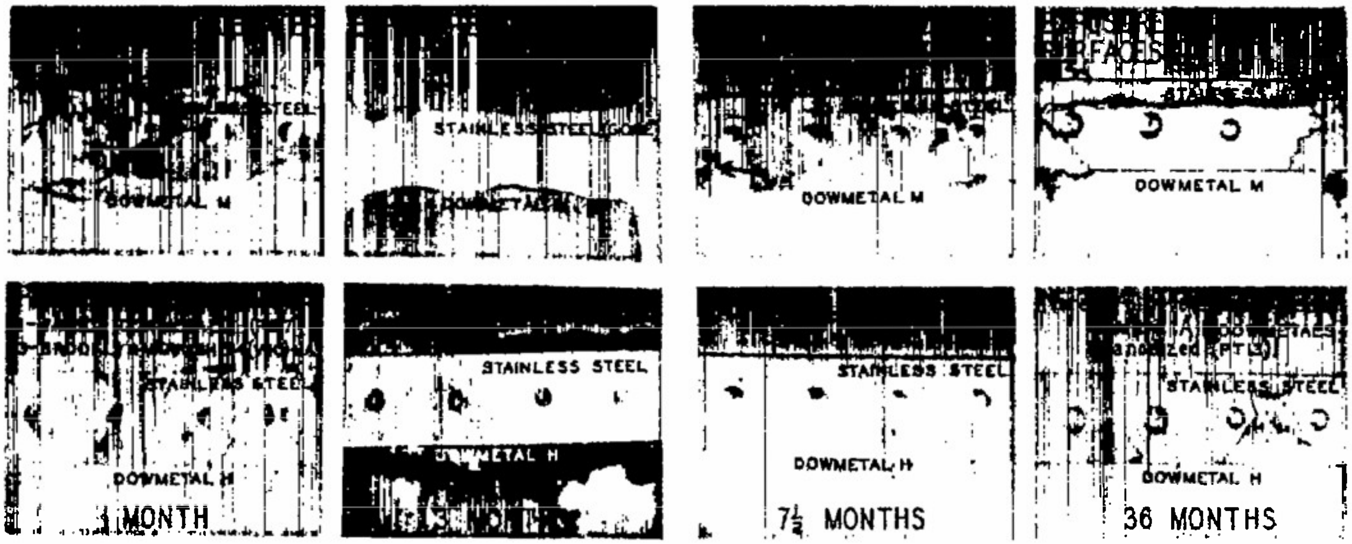


Figure 34.- Painted panels, comparable with those shown in figure 33, after exposure at Hampton Roads, Va. Note that the paint afforded little protection against tidewater exposure, and that it began to fail to adhere to the stainless steel strips after 7-1/2 months of weather-exposure (arrows). x 1/2.

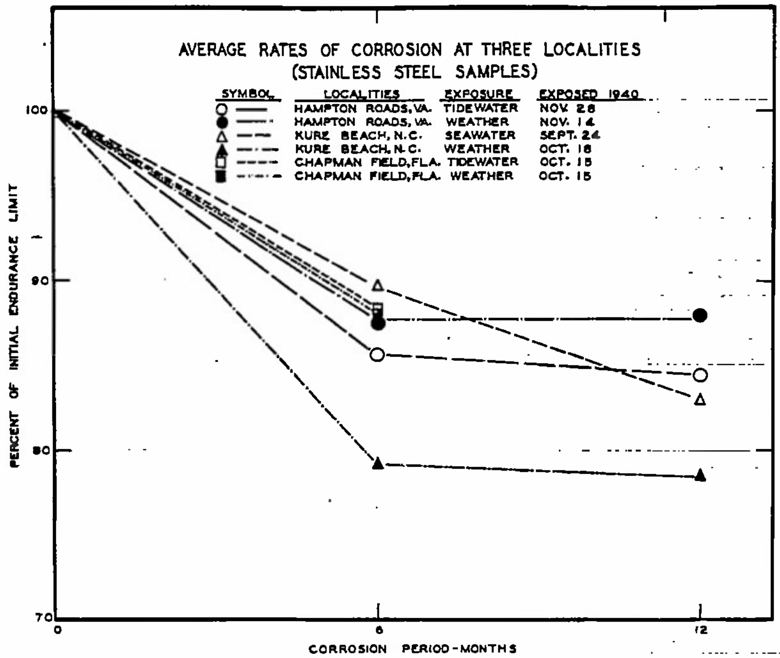
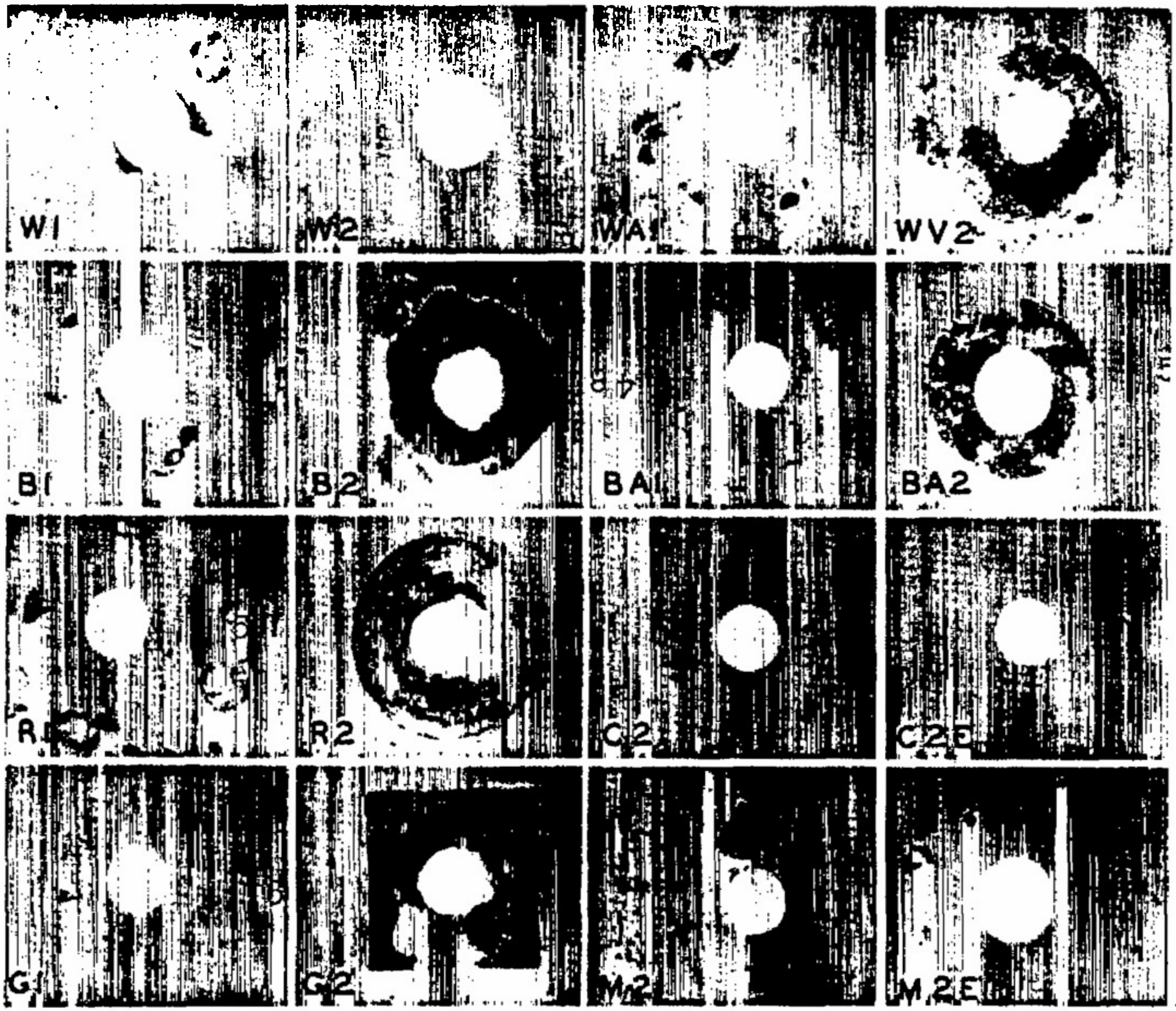


Figure 35.- The average percentage of loss of endurance limit of stainless steel panels exposed to the weather or tidewater at Hampton Roads and Chapman Field, or to the sea water at Kure Beach is shown to be very similar, the deviation being less than ± 3 percent. Panels exposed to the weather at Kure Beach were the ones most severely corroded.



(x1)

Figure 36.- The four-point method of supporting panels in the tidewater racks served to prevent corrosion caused by contact with the supporting medium. The symbols:- W, wood, cypress; B, bakelite; R, hard rubber; G, glass; C, copper; M, monel metal; A separator painted with aluminum varnish; V, separator painted with clear varnish; E, mounted to permit an electric circuit; 1, four-point contacts; 2, solid contact of 1 square inch area.

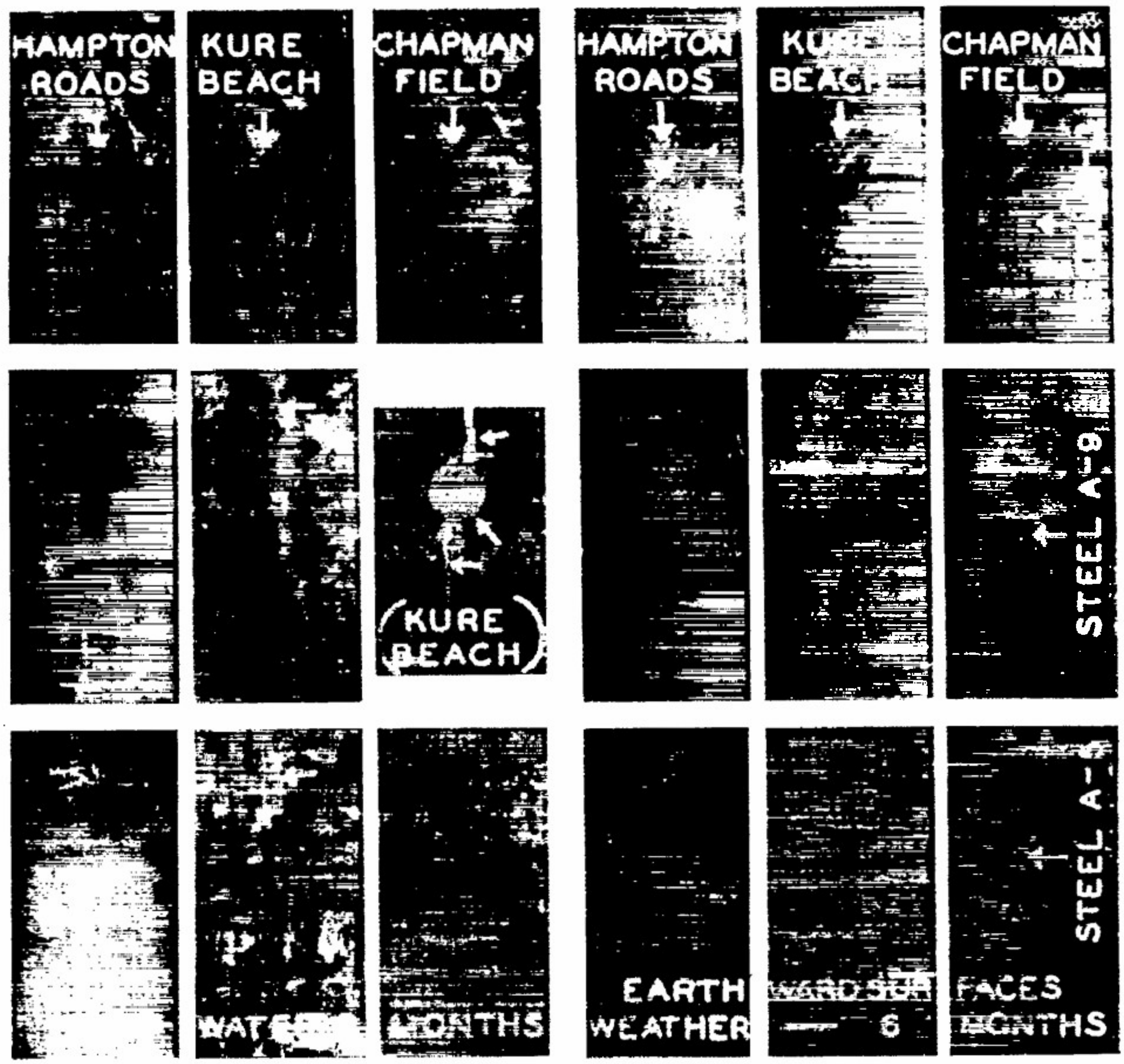


Figure 37.- Stainless steel panels exposed to the weather and tidewater as indicated. Panels exposed to sea water at Kure Beach exhibited more evidence of the action of organisms, but were rusted only where held by bakelite supports (arrows) or in streaks originating at those areas. x 1/4.

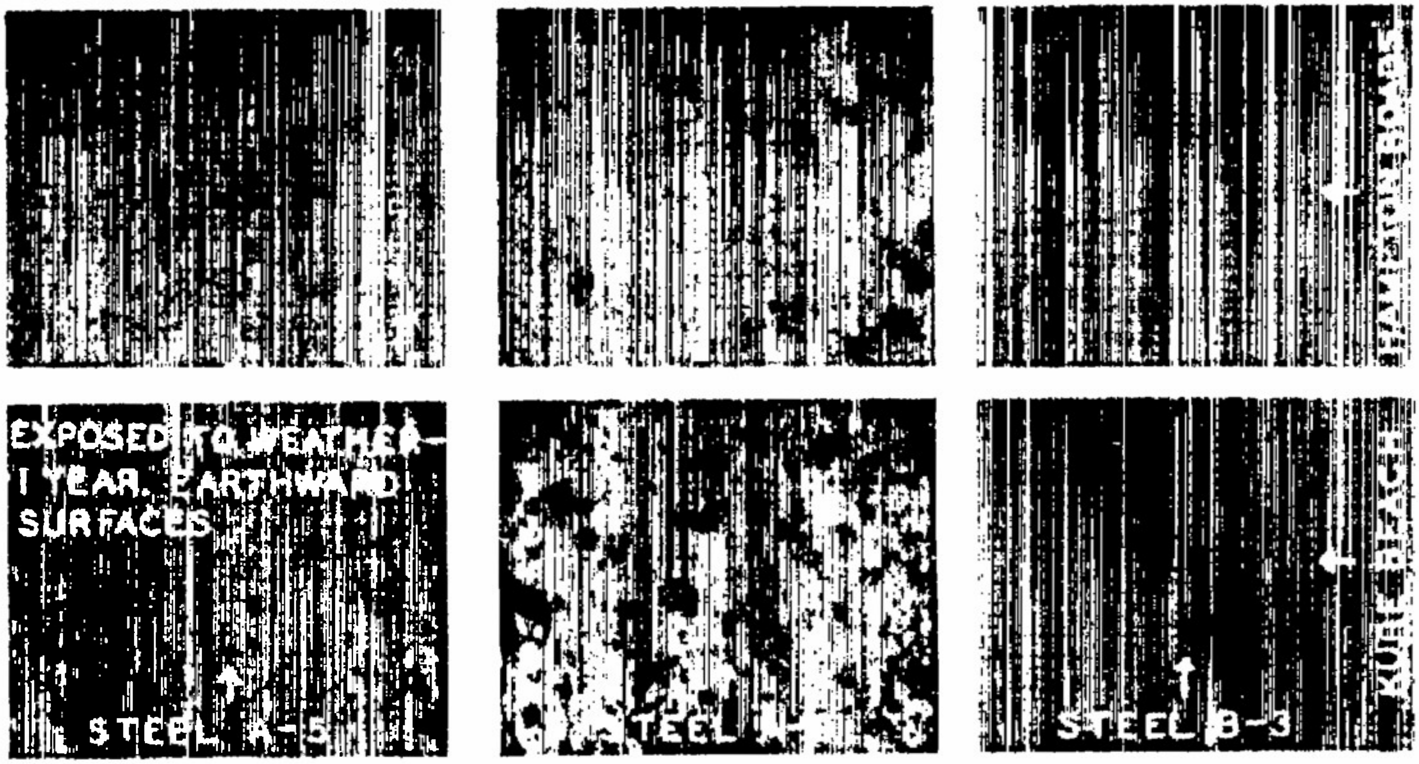


Figure 38.- Stainless steel panels, after a year's weather-exposure, were much more rusted at the Kure Beach site than at Hampton Roads. The molybdenum containing steel, however, was very much less rusted than the others. x 3/5.

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ABSTRACT

Object of investigation was to establish relative resistance to corrosion of chromium-nickle alloys of type 18:8 with and without columbium, molybdenum, and titanium; information on locality exposure and shot-welding of surface treatments was to be obtained. Panels were cold-rolled and surface passivated in 20% nitric acid. They were exposed to tidewater and weather for three years. Endurance limit decreased rapidly in the first six months. Test results are given in tables and graphs.

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